PRODUCER GAS

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AND
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With F. Cleaves'
Compliments
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PREFACE

In the thirty odd years which I have devoted to the subject of Producer Gas and its applications, it has been my good fortune to make many pleasing friendships here and in other countries. Like most people, I have had my disappointments and troubles, but I have been greatly encouraged and assisted by the kind consideration and co-operation with which I have met. I feel especially indebted to Professor Ayrton, because he first gave me a helping hand in the most disinterested way. In 1881 I exhibited my apparatus at the Paris Electrical Exhibition, and there and then he volunteered to give a lecture on the subject in the Salle du Congrès, in order to draw attention to what was being done, and to what it might lead to. I trust that the progress since made may be considered a justification of the interest he then awakened in the subject.

I am also indebted to some of the makers of gas-engines. Not unnaturally they were at first disposed to think that it would not be to their interest to work their engines with producer gas, as it was so much weaker than town gas: the reputation of the engine itself was not then fully established, and they were fearful lest by using producer gas they might add to the difficulties with which they had to contend. That was in the days of small engines, when the consumption of gas was not great, and when the cost of the gas was of minor importance. Later they realised that the future of gas-power depended largely on producer gas, and I had the advantage of their co-operation.

I am fully conscious that the growing importance of producer gas demands a more exhaustive treatment than I have been able to give it in the limited time at my disposal. I am also afraid that in the course of what I have written I may have given undue prominence to what I have done myself; but, frankly, I have endeavoured to avoid doing so, and I would ask that allowance be made for the fact that for many years my mind has been soaked with the subject and that to a considerable extent I have been obliged to seek results from trials and experiments I made myself.

Producer gas has now a recognised position in practical work, and I am confident that in the near future its adoption will be greatly extended; it is, therefore, desirable that its production and application should be considered theoretically as well as practically. Mere rule of thumb cannot be right. I trust, therefore, that this little work may be the forerunner of some more complete and exhaustive treatment of the subject. There are numerous books on the theory and practice of the gas-engine, but so far as I am aware there is no complete work on producer gas.

I should add that the pressure of business has made such demands on my time that I could not have undertaken the preparation of what I now venture to put forward without the help of my assistant, Mr. Larter, and I have to thank him for the care and thought he has brought to bear on the subject.

I also desire to thank the various makers of gas-plants who have been good enough to send me illustrations and particulars of their apparatus.

J. EMERSON DOWSON.

ASHTEAD,
September, 1906.

PREFACE TO SECOND EDITION

I CANNOT but feel gratified that there should be need for a second edition of this book so soon after its first publication, and I thank my readers and my reviewers for the kindly welcome they have given to what I ventured to put forward.

It confirms my opinion that interest in the important subject of Producer Gas is awakening, and I feel sure that the more it is understood—theoretically and practically—the more the gas will be used, not only for driving engines, but for heating work in many industrial processes.

There were a few typographical errors in the first edition which have now been corrected. Some new Figures have been added, and additions have been made in the subject-matter, but special attention has been given to Chapters VII. and VIII. on Suction Plants. The latter are rapidly increasing in favour, and they have been treated more fully than in the earlier edition.

J. E. D.

June, 1907.

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INTRODUCTION

The use of Producer Gas is now so extensive, it is required for so many different purposes, and is made with so many kinds of fuel, that we venture to think the time has arrived to take a comprehensive view of the whole subject.

A good deal is known about the practical working of gas producers in connection with furnaces and gas-engines; but much less is known about the thermo-chemistry of the subject, and the principles and conditions on which the successful working of gas producers depends. We have, therefore, devoted our first three chapters to a consideration of the formation of producer gas from a strictly theoretical point of view, and it seems to us that this is the only way of getting to understand the rather complicated conditions under which the best gas can be made. Moreover, it is essential that the principles which underlie the process should be clearly grasped if we wish to attain the best results. On these lines we have discussed the subject in various aspects, and have shown what is the theoretical best which might conceivably be attained under various conditions of working. We have then compared with the theoretical best the actual results obtained in practice, in known types of gas producers. These comparisons have led us to consider various side issues, and we think they will not be without interest.

In connection with furnace work it was Bischof of Mägdesprung in the Harz who made the first gas producer; but no great advance was made until Frederick Siemens brought out his combination of gas producer and regenerative furnace in 1857. This important invention and other subsequent improvements were introduced in this country by his brother, the late Sir William Siemens, and we are chiefly indebted to the latter for the great impetus he gave to the use of producer gas for furnaces requiring high and uniform temperatures. He was both scientific and practical, and he proved by actual results, on a full working-scale, that there was not only a saving in fuel by converting it into a combustible gas (before burning it in the furnace), but that many important operations in industrial processes could be performed with gas-heated furnaces, which could not be effected by direct firing with solid fuel. Various modifications and improvements in gas producers and furnaces have since been made by others, and each notable type is discussed; but we have purposely avoided mere details or alterations in the form of construction in order that the main principles should be kept steadily in view.

We have shown that for furnace work the gas is used in bulk, and that the crude gas is taken direct from the producer to the furnace without being cooled or cleaned. For smaller work, as for instance where the gas must pass through small cocks and burners, the gas must be specially treated before it is used, and in 1878 Mr. J. E. Dowson devised a complete gas-plant for this purpose. He had specially in view the making of a fuel-gas strong enough and clean enough to be used for factory and domestic work, and this branch of work has been very successful.

A still more important development in the use of producer gas has taken place in connection with gas-engines. Mr. Dowson read his first paper on the subject in 1881, at the York Meeting of the British Association for the Advancement of Science, and he then showed a set of his plant working a 3 H.P. Otto gas-engine. It was on this occasion that the late Sir Frederick Bramwell made his memorable prophecy to the effect that in fifty years the gas-engine would have superseded the steam-engine. We need hardly concern ourselves at present with the downfall of the steam-engine, our opinion being that the gas-engine and the steam-engine have certain well-defined characteristics, and that each is more or less suitable than the other for certain kinds of work. We can afford to await the result of actual experience;

but we may say that after the lapse of no more than half the time prophesied there has certainly been a remarkable development, not only in the use of gas-power in lieu of steam, but also in the size of gas-engines. The horizontal type of Otto engine was patented in 1876, and we believe we are right in saying that at the time of the York Meeting, above referred to, there was no gas-engine working which developed more than about 12 B.H.P., certainly not more than 20 B.H.P. It is also certain that no gas-engine, other than the 3 H.P. at York, had then worked with producer gas. At the present time, however, there are many gas-engines of 1500 and 2000 B.H.P. working satisfactorily with producer gas or blast-furnace gas; and the number of engines working with producer gas is very considerable.

During the last few years an interesting development has taken place in the gas-plants used with gas-engines. We refer to what is generally known as the *suction* type of plant; and as this branch of the subject is new, and several interesting problems are involved in it, we have examined them closely in order that the right principles to be followed may be clearly understood. When it was proved that a gas-engine could be worked satisfactorily and economically with producer gas, the makers of gas-engines realised that it would be worth while to construct larger engines than could be worked profitably with such an expensive fuel as ordinary town lighting gas. Since the introduction of the suction-plant there has been a still more intimate connection between the gas-plant and the engine, and one consequence of this has been that greater attention has been given to the design and adjustments of the engine, so that the comparatively weak producer gas may be used to better advantage. For a long time the peculiarities of producer gas were not sufficiently considered; the engine was designed for town gas, and its weaker rival had more or less to take its chance. We have endeavoured to bring together the theoretical and practical considerations on which a gas-power plant depends, and although good results have already been attained, we feel sure that further advance will be made now that skilled attention is being given to the subject and engine-makers realise that the future of their engines will to a great extent depend on their working with producer gas. The thermodynamic problems connected with the gas-engine alone are numerous and difficult, and for some time past they have engaged the attention of some of the best experimenters in this country and in others. Less attention has been given to the plant which supplied the engine with gas, but this branch of the subject will well repay closer investigation.

We are convinced that the use of producer gas will be greatly extended, and we say this because we believe that for many purposes the conversion of solid fuel into gas is right in principle and right in practice. Besides this, there is the encouraging fact that the subject is better understood and better appreciated than it was twenty or even ten years ago. To a certain extent this may be attributed to the spread of technical instruction, but it is also largely due to the fact that the price of coal has nearly doubled in many manufacturing centres, while at the same time competition with other countries has greatly increased. These two facts alone have made it necessary for manufacturers to consider closely any saving in fuel which can be effected in a simple and practical manner. They are now realising that the use of producer gas for heating and power is not a mere fad, but a useful and economical system; and it is tolerably certain that what is cheapest and most efficient will in the end be generally adopted.

PRODUCER GAS

CHAPTER I

THEORY OF PRODUCER GAS

Technically, "producer gas" is understood to mean the gas which is obtained by the partial combustion of fuel in a gas producer. This is not a very happy expression, as strictly speaking a retort used for distilling coal-gas may be said to be a gas producer. It is, however, an accepted term among engineers, and it would be somewhat pedantic to quarrel with it now that it is a common expression with a fairly definite meaning. A gas producer may be defined as an apparatus for converting solid fuel into a combustible gas; and the gas produced is usually a mixture in varying proportions of carbon monoxide, hydrogen, gaseous hydrocarbons (chiefly methane or marsh gas), carbon dioxide, and nitrogen. The first three of these constituents are combustible, and the value of the gas as a fuel depends on the proportions in which they are present; the carbon dioxide and nitrogen are diluent gases which lower the flame temperature of the combustible gases when they are burnt.

Producer gas can be obtained from almost any carbonaceous fuel, and the kind of fuel used depends, not only on the purpose for which the gas is to be used, but on its cost and the ease with which it can be procured in different localities. In practice the gas is generally made from bituminous or semi-bituminous coal, or from anthracite or coke; but for certain purposes brown coal, lignite, peat, charcoal, etc., are used. The composition of the gas is largely influenced by the nature of the fuel, and this will be more fully discussed hereafter.

Speaking generally, producer gas is made by forcing or drawing air, with or without the addition of steam or water-vapour, through a deep bed of fuel in a closed producer. The fuel is gradually consumed and the gas made is led away to wherever it is required. An important characteristic of the process is that no external heat is applied to the producer, as in the case of an ordinary gas retort; when once the burning of the fuel *inside* the producer has been started the air which is used to make the gas keeps up a continuous process of combustion, and a sufficiently high temperature is maintained to decompose the steam and to effect other necessary reactions which will be presently described.

The most important constituent of the fuels commonly used for making producer gas is carbon; and for the purpose of explaining the theory of the process we will, in the first instance, consider the action of air alone on pure carbon in a producer. Gas made by burning charcoal with a blast of air (without steam) approximates closely to this, but to simplify the case, we will suppose that the fuel used is carbon. As is well known, four-fifths of the volume of the atmosphere consists of nitrogen, and although this affects the temperature attained, and therefore modifies the reactions to a certain extent, it does not in any way affect the *quantities* of heat with which we are concerned. We will, therefore, neglect these considerations for the moment, and merely consider the combination which takes place between oxygen and carbon. If there were a shallow fire in the producer and an abundant supply of air the carbon would be completely oxidised; the product of this complete combustion would be carbon dioxide, while the quantity of heat developed from the combustion of 12 kilos of carbon would be 97,600 calories:—

$$C + O_2 = CO_2 + 97{,}600 \text{ calories.}^1 \quad . \quad . \quad . \quad (1)$$

But if there were a considerable depth of carbon in the producer (as there should always be in practice), the resulting gas would be carbon monoxide instead of carbon dioxide, for when there is an excess of highly heated carbon the carbon dioxide formed in the lower part of the fire is reduced to carbon monoxide:—

$$CO_2 + C = 2CO - 38{,}800 \text{ calories.} \quad . \quad . \quad . \quad (2)$$

---

[1] Unless otherwise stated, the term "calorie" should be understood to mean the large calorie, or kilogram heat unit, = 3·968 British thermal units.

In this case, heat must be applied in order that the reaction between carbon dioxide and carbon may take place, and the quantity of heat required is 38,800 calories when 12 kilos of carbon react with the carbon dioxide formed by the complete combustion of another 12 kilos of carbon.

Carbon monoxide may also be formed by the direct combination of the carbon with oxygen:—

$$2C + O_2 = 2CO + 58{,}800 \text{ calories.} \quad . \quad . \quad . \quad (3)$$

Actually both these reactions may and probably do occur.

The *raison d'être* of the producer is to bring about a partial combustion of the fuel, *i.e.* the conversion of the carbon to carbon monoxide, either by reactions (1) and (2) or by reaction (3). If the combustion were complete, the gas which leaves the producer would be incombustible and useless as a heating agent.

The action of the producer will be better understood by referring to the accompanying Fig. 1. In this **A** represents the firebars or grate, **B** is the air inlet, **C** is the column of fuel, **D** is a hopper with close-fitting valve through which the fuel is introduced, and **E** is the gas outlet. After the

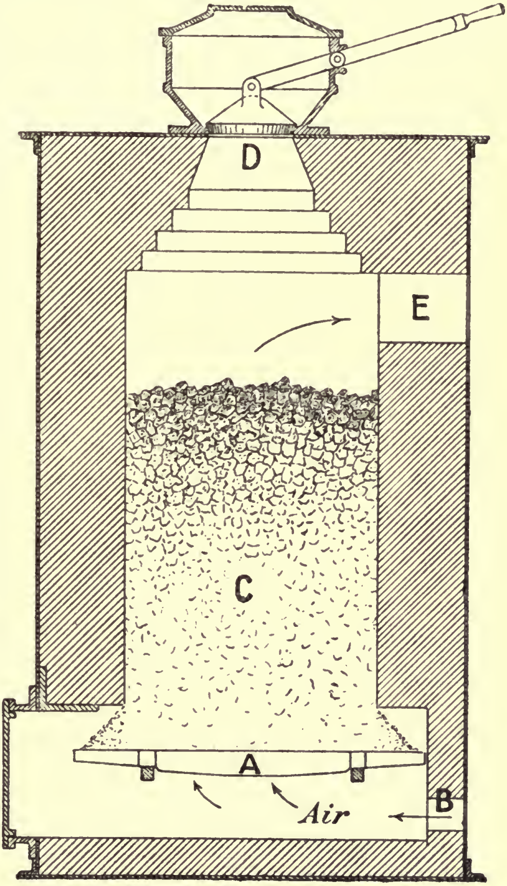

Fig. 1.—Gas-producer working with air only.

fire has been lighted, and built up to the height required to ensure the necessary reactions, the gas produced passes away through the outlet E and can then be conveyed in a pipe or flue wherever it may be required.

It is easy to see that the same result is attained by either of the two methods described for producing carbon monoxide. On the one hand, 24 kilos of carbon are converted to carbon monoxide by direct union with oxygen, the heat liberated being 58,800 calories, according to equation (3). On the other hand, 12 kilos of carbon are converted to carbon dioxide, and 97,600 calories are set free, according to equation (1); and subsequently the whole of this carbon dioxide reacts with another 12 kilos of carbon to form carbon monoxide, and 38,800 calories are absorbed, in accordance with equation (2). The final result of this twofold process is the conversion of 24 kilos of carbon to carbon monoxide and the liberation of 97,600 − 38,800 = 58,800 calories, since the only heat available to enable reaction (2) to take place is the heat liberated during the conversion of the 12 kilos of carbon to carbon dioxide. The two ways in which the carbon may be converted to carbon monoxide are represented by the following equations :—

In the first case—

$$2C + O_2 = 2CO + 58{,}800 \text{ calories.}$$

In the second case, the following reactions take place in succession :—

$$(a) \quad C + O_2 = CO_2 + 97{,}600 \text{ calories,}$$
$$(b) \quad CO_2 + C = 2\,CO - 38{,}800 \text{ calories;}$$

the final result of these two processes being expressed by the equation—

$$C + O_2 + C = 2CO + 97{,}600 - 38{,}800 = 58{,}800 \text{ calories.}$$

In the same way, it may be shown that the final result of the complete combustion of carbon is the same whether it takes place in one stage (reaction 1) as in an open fire, or whether carbon monoxide is first formed as in a producer and then burnt to carbon dioxide. In the former case we have 12 kilos of carbon converted to carbon dioxide, with the liberation of 97,600 calories; in the latter case the same amount of heat is liberated in two successive reactions. Taking 24 kilos of carbon, the changes are represented by the equations—

$$2C + O_2 = 2CO + 58{,}800 \text{ calories,}$$
$$2CO + O_2 = 2CO_2 + 136{,}400 \text{ calories,}$$

and the final result of the two processes is the conversion of 24 kilos of carbon to carbon dioxide, with the liberation of 195,200 (2 × 97,600) calories.

We see from this that when carbon is converted to carbon monoxide in the producer about 30 per cent. of the heat of combustion of the carbon is liberated; the remaining 70 per cent. will be liberated when the carbon monoxide is afterwards burnt to carbon dioxide in a furnace or engine, etc. As this is the theoretical best when using air only, it may be assumed that the practical best is still less favourable, and *primâ facie* the performance does not seem a promising one. It should, however, be understood that not all the heat set free in a producer need be lost; a large proportion may be carried away in the form of sensible heat by the gas, which leaves the producer at a high temperature; and if the gas can be used while it is hot not much of this sensible heat will be lost. The amount of the loss will depend on the extent to which the gas is cooled before it is used. Theoretically, there is no reason why the use of producer gas in place of solid fuel should necessarily involve a loss of part of the heat available by the direct combustion of the solid fuel, although a considerable proportion of that heat is liberated during the conversion of the solid fuel into producer gas. In practice, however, this economy cannot be fully realised, but it can be approached. The chief difficulty lies in the fact that it is not possible to convey sensible heat from one point to another without loss, especially when the temperatures are high.

If we take into consideration the quantity of nitrogen present in the air used in the producer, it is easy to calculate for our assumed case the composition of the best gas that can be made. Following the equation (3), 24 kilos of carbon yield two volumes (44·64 cubic meters) of carbon monoxide, and one volume (22·32 c.m.) of oxygen is required for the process. The atmosphere contains almost exactly 21 per cent. by volume of oxygen, and we may consider the remaining 79 per cent. to consist of nitrogen.[1] The oxygen used in the reaction is therefore associated with $\frac{79}{21}$ or 3·76 volumes (83·92 c.m.) of nitrogen, and the producer gas will consist of 2 volumes of carbon monoxide mixed with 3·76 volumes of nitrogen. Its composition will therefore be—

Carbon monoxide	34·7	per cent. by volume.
Nitrogen	65·3	" "
	100·0	

and the volume of gas obtained from 24 kilos of carbon will be 44·64 + 83·92 = 128·56 cubic meters, or 5·36 c.m. per kilo of carbon. The densities of carbon monoxide and nitrogen are alike, so that the percentage composition by weight will be represented by the same figures as for the volumes. The calorific power of this gas will be 1057 calories per cubic meter, or 118·8 Brit. T.U. per cubic foot.

It will also be well to determine the temperature which would be attained in a producer yielding gas of the above composition, although the calculation can only be approximate, as several assumptions must be made. In the first place, part of the heat given out in the producer would be lost by radiation, conduction, etc., and some estimate must be formed of its quantity. We shall probably not be far wrong in assuming this to be 8 per cent. of the heat of combustion of the fuel. The sensible heat of the gas as the latter leaves the producer would therefore be about 22 per cent. of the heat of combustion, and taking 12 kilos of carbon as a convenient unit for purposes of calculation, this sensible heat would amount to 97,600 × 0·22 = 21,472 calories. The quantity of carbon monoxide formed is 28 kilos, and it is mixed with 53 kilos of nitrogen. The specific heats of the two gases at constant pressure are almost identical, viz. 0·244 and 0·245, and assuming them to be constant over the whole range of temperature, the heat required to raise the temperature of the 81 kilos of producer gas through 1° C. will be 81 × 0·245 = 19·845

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[1] As a matter of fact, dry air has the following composition by volume:—Oxygen, 20·9 per cent.; nitrogen, 78·2 per cent.; argon, etc., 0·9 per cent. (The small amounts of carbon dioxide and ammonia are neglected.)

calories; the temperature of the hot gases would accordingly be $\frac{21472}{19\,845} = 1080°$ C.

It will be seen from this that the temperature in a producer worked with a blast of air alone must of necessity be high. In the actual working of the producer there is always a certain quantity of carbon dioxide in the gas produced and this involves a still greater development of heat in the producer. With such high temperatures serious practical difficulties present themselves, and they will be further considered in subsequent chapters.

To avoid these practical difficulties, and for other reasons, the almost invariable practice is to add to the air sent into the producer a certain quantity of steam, or aqueous vapour, as indicated in Fig. 2. In this **A** represents the grate or firebars; **B**, the inlet for steam and air; **C**, the fuel; **D**, the hopper through which the fuel is introduced; and **E**, the gas outlet. There is always some moisture in the air itself, but this is not nearly sufficient and it is usual to generate steam specially for this purpose. We will now consider theoretically the case of a producer in which

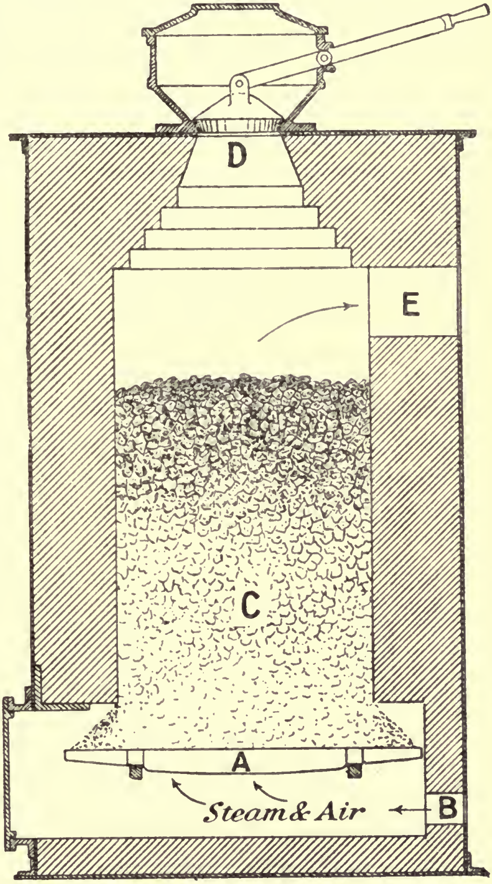

Fig. 2.—Gas-producer working with steam and air.

pure carbon is converted into gas by means of air mixed with steam. In other words, we will consider how steam reacts with the substances with which it comes in contact in the producer, viz. carbon, carbon monoxide, and carbon dioxide. When steam (H_2O) interacts with carbon at a sufficiently high temperature it is decomposed and an equal volume of hydrogen is produced; the oxygen of the steam combines with the carbon to form either carbon monoxide or carbon dioxide, according to the conditions under which the reaction takes place. Now, when 2 kilos of hydrogen combine with oxygen to form 18 kilos of water-vapour the quantity of heat liberated is 58,200 calories, and when this water-vapour is decomposed by the action of carbon at high temperature, or by any other means, an equal amount of heat is absorbed. The combination of the oxygen of the steam with the carbon is, however, accompanied by the evolution of heat, according to either of the equations (1) or (3), and the thermal effect of the decomposition of steam by carbon is equal to the sum of the thermal effects of the two separate processes. In the first case, when the products of the reaction are hydrogen and carbon monoxide, the quantity of heat liberated by the formation of the latter from 16 kilos of oxygen is 29,400 calories, and the equation may accordingly be written—

$$\begin{aligned} H_2O + C &= H_2 + CO - 58{,}200 + 29{,}400 \\ &= H_2 + CO - 28{,}800 \text{ calories.} \quad . \quad . \quad (4) \end{aligned}$$

In the second case, when the products formed are hydrogen and carbon dioxide, we must first suppose that 36 kilos of steam are decomposed, yielding 4 kilos of hydrogen and 32 kilos of oxygen, with the absorption of 116,400 calories. The combination of the 32 kilos of oxygen with carbon to form carbon dioxide liberates 97,600 calories, and the reaction is therefore represented by the equation—

$$\begin{aligned} 2H_2O + C &= 2H_2 + CO_2 - 116{,}400 + 97{,}600 \\ &= 2H_2 + CO_2 - 18{,}800 \text{ calories.} \quad . \quad . \quad (5) \end{aligned}$$

It will be observed that in both cases there is a large absorption of heat, and it is at once apparent why the addition of even small quantities of steam to the air-blast of a producer reduces the working temperature. Part of the sensible heat is absorbed by the reactions which take place between the steam and the incandescent carbon, so that the gas leaves the producer at a lower temperature than is the case when air alone is used; the heat so absorbed is stored up in the gas, and is again set free when the gas is burnt. In other words, the effect of the presence of steam in the air-blast is that a smaller proportion of the total heat of combustion of the fuel is liberated in the form of sensible heat in the producer, and a larger proportion is represented by the heat of combustion of the producer gas. A rough indication of the effect produced on the fire in the producer, when steam is used, is shown in Fig. 2; in this the column of fuel is darker (*i.e.* cooler) than in Fig. 1, where no steam is used. This effect is especially noticeable near the top of the fuel.

It should be clearly understood that from the point of view of the heat quantities involved the use of steam in a gas-producer is simply a means for absorbing the sensible heat developed by the partial combustion of carbon, and storing it for future use. Obviously there can be no actual increase of the total amount of heat which can be obtained from a given quantity of fuel. From equation (4), it would appear that from 12 kilos of carbon there can be obtained (theoretically) a quantity of gas which when burnt will give out 58,200 calories by the combustion of the hydrogen, and 68,200 calories by the combustion of the carbon monoxide which it contains, or 126,400 calories in all; although the original 12 kilos of carbon would only yield 97,600 calories when burnt in air. In consequence of the action of steam on the carbon there is apparently an increase of 28,800 calories in the quantity of heat which can be obtained by the combustion of the 12 kilos of carbon; the explanation is that exactly 28,800 calories must be supplied in order that the reaction represented by equation (4) may take place. The heat which is required for this is provided by the union of carbon with the air in the blast (equations 1 and 3), and if it were not made use of in this manner it would be partly lost by radiation, and partly carried away as sensible heat by the producer gas.

Besides avoiding excessive heat in the producer the use of steam has the further practical advantage that a gas of considerably greater calorific power per unit volume can be obtained than is possible when air alone is used. In the latter case it has already been shown that every volume of carbon monoxide in the gas is mixed with 3·76 volumes of nitrogen; but equation (4) shows that when steam is used the gas which is formed by its decomposition is free from nitrogen. It follows that in a producer burning carbon in a mixed blast of air and steam the greater the quantity of steam decomposed in accordance with equation (4), relatively to the quantity of carbon consumed in accordance with equation (3), the greater will be the proportion of the combustible gases (carbon monoxide and hydrogen) to the total volume of producer gas formed; and the calorific power of unit volume of the producer gas will accordingly be greater also. A similar statement will be equally correct if the steam admitted to the producer is decomposed according to equation (5). In this case the hydrogen (which has approximately the same calorific power per unit volume as carbon monoxide) is mixed with an equal volume of the incombustible gas, carbon dioxide; but since the carbon monoxide, formed by the action of air on the carbon, is mixed with nearly twice its own volume of incombustible gas (in this case nitrogen) the use of hydrogen will in this case also increase the calorific power of the gas, though not to the same extent for a given ratio of steam to air. When it is desired to obtain a richer producer gas containing as high a proportion as possible of combustible gases and having a high calorific power it becomes important to decompose as much steam as possible in the producer by the reaction which is expressed in equation (4). The decomposition of steam with the formation of hydrogen and carbon dioxide, as in equation (5), will have a similar effect, but however great the proportion of steam to air may be the increase of calorific power due to the use of steam will necessarily be less than when the interaction takes place in accordance with equation (4).

In order to determine what is the theoretical limit to which this advantage can be pushed, we will assume that all the sensible heat of the gases leaving the producer and all the heat which would otherwise be lost by radiation are made use of in raising the steam and in heating the blast; that is to say, we will assume that there are no heat losses, so that the whole of the heat of combustion of the fuel will be available as heat of combustion of the gas which is produced. This will be the case only if the quantity of heat absorbed by the interaction of steam and carbon be just equal to the quantity of heat evolved by the formation of carbon monoxide from carbon and the oxygen of the air in the blast. The maximum quantity of steam which can be decomposed is fixed by this consideration; if more steam than this were decomposed the temperature of the producer would fall rapidly, until it became too low for the reaction to take place; if the quantity of steam decomposed were too small the temperature of the producer would rise, and the total heat of combustion of the gas would be less than that of the fuel from which it was obtained.

Under the conditions which we have assumed, for every 12 kilos of carbon converted to carbon monoxide in accordance with equation (3), there are 29,400 calories available to enable the reactions between steam and carbon to take place. The richest gas will be obtained if the working conditions can be regulated so that the steam and carbon interact wholly according to equation (4). In this case, 28,800 calories are required for the decomposition of 18 kilos of steam by carbon, and to this must be added the latent heat of the steam, since we have supposed that the steam is generated by the sensible heat of the producer gases, and therefore ultimately by the heat which is evolved by the formation of carbon monoxide from carbon and atmospheric oxygen in the producer. Making the calculation in this way we shall find the composition of the ideal producer gas which can theoretically be made in a self-contained system, where the only source of heat is the oxidation of carbon in the producer, and where no heat is supplied in any other way. This case is therefore not quite on the same lines as many practical cases, where steam is taken from an independent steam boiler.

The latent heat of 18 kilos of water-vapour at 20° C. amounts to 10,800 calories, so that the heat required to convert 18 kilos of water at 20° C. to steam, and to decompose the steam in the producer, with the formation of carbon monoxide and hydrogen, is $28{,}800 + 10{,}800 = 39{,}600$ calories. The quantity of steam which theoretically can be decomposed is—

$$18 \times \frac{29{,}400}{39{,}600} \text{ or } 18 \times 0{\cdot}74 \text{ kilos.}$$

for every 12 kilos of carbon converted to carbon monoxide by the air in the blast. The gas which is formed will be made up in the following way :—

Carbon monoxide .	1·00 vol. (22·32 c.m.)	from the reaction of carbon with the air of blast.
Nitrogen	1·88 ,,	
Carbon monoxide .	0·74 ,,	from the reaction of carbon with the steam of blast.
Hydrogen	0·74 ,,	
Total . .	4·36 ,,	

Its percentage composition by volume is as follows :—

Carbon monoxide . . .	39·9	combustible gases = 56·9
Hydrogen	17·0	
Nitrogen	43·1	
Total . .	100·0	

and its calorific power is 1740 calories per cubic meter or 195·6 Brit. T.U. per cubic foot.

The quantity of gas obtained amounts to 4·36 volumes, or 4·36 × 22·32 c.m.; the carbon used is 12 kilos consumed by the air of the blast, and 12 × 0·74 = 8·88 kilos used in the reaction with steam, making a total of 20·88 kilos of carbon. The yield of gas is therefore—

$$\frac{4{\cdot}36 \times 22{\cdot}32}{20{\cdot}88} = 4{\cdot}65 \text{ c.m. per kilo of carbon burnt.}$$

For every 20·88 kilos of carbon consumed, the weight of steam decomposed is 18 × 0·74 = 13·32 kilos, or 0·64 kilo of steam per kilo of carbon.

Comparing this result with that obtained when the blast consists of air alone (p. 6), we see that when steam is added to the blast and decomposed in accordance with equation (4), a rather smaller volume of a much richer gas is obtained from each kilo of carbon consumed.

Without at present discussing in detail the conditions under which the various reactions take place, it may be mentioned that in order to obtain only hydrogen and carbon monoxide from the reaction between steam and carbon a high temperature is necessary; but for practical reasons it may be more advantageous in some cases to work at a lower temperature, and to allow the decomposition of the steam to take place with the formation of carbon dioxide and hydrogen (equation (5)). This course is, in fact, essential when it is desired to recover the nitrogen of the fuel in the form of ammonia, as in the Mond and other forms of recovery plants.

Proceeding on the same lines as above, we can determine the theoretical composition of a producer gas made in this way. According to equation (5), 18,800 calories are required for the decomposition of 36 kilos of steam in the producer. Adding to this the latent heat of the steam, 21,600 calories, the total heat required to convert 36 kilos of water at 20° C. to steam, and to decompose the latter in the producer, is 40,400 calories. The quantity of steam which can be decomposed is—

$$36 \times \frac{29{,}400}{40{,}400} = 36 \times 0{\cdot}73 = 26{\cdot}88 \text{ kilos}$$

for every 12 kilos of carbon consumed in accordance with equation (3).

The gas therefore consists of—

Carbon monoxide . .	1·00 vol.	(containing 12 kilos carbon)	from the reaction between carbon and the air of the blast.
Nitrogen	1·88 ,,		
Hydrogen	1·46 ,,		from the reaction between carbon and steam.
Carbon dioxide . .	0·73 ,,	(containing 12 × 0·73 = 8·76 kilos of carbon)	
Total . .	5·07 ,,	(containing 20·76 kilos carbon)	

and the quantity of steam used is $\frac{26{\cdot}88}{20{\cdot}76}$ or 1·29 kilos per kilo of carbon.

The percentage composition of this gas by volume is as follows:—

Carbon monoxide . . .	19·7	combustible gases = 48·5
Hydrogen	28·8	
Carbon dioxide	14·4	diluent gases = 51·5
Nitrogen	37·1	
Total . .	100·0	

and its calorific power is 1490 calories per cubic meter or 167·5 Brit. T.U. per cubic foot. The yield of gas is 5·07 × 22·32 c.m. from 20·76 kilos of carbon or 5·45 c.m. per kilo of carbon consumed.

The volume of gas obtained is thus almost identical with the volume of gas which theoretically can be obtained from carbon and air alone, but as in the case previously considered the calorific power of the gas is considerably higher when steam is used.

In the examples which have been discussed it has been tacitly assumed that the steam reacts only with the solid carbon in the producer, and that the gases formed do not interact among themselves. As a matter of fact, however, this assumption is not strictly correct. If a mixture of equal volumes of hydrogen and carbon dioxide be raised to a high temperature, such as that which prevails in a gas producer, part of the gases will interact to form carbon monoxide and steam, with an absorption of heat, thus—

$$CO_2 + H_2 = CO + H_2O - 10{,}000 \text{ calories} \quad . \quad (6a)$$

On the other hand, a mixture of carbon monoxide and steam under the same conditions will react to a certain extent in the opposite sense, forming carbon dioxide and hydrogen with liberation of heat—

$$CO + H_2O = CO_2 + H_2 + 10{,}000 \text{ calories} \quad . \quad (6b)$$

In each case, the extent to which the reaction proceeds will depend on the temperature and the relative quantities of the reacting gases—carbon dioxide and hydrogen in the former case, carbon monoxide and steam in the latter. At a given temperature and with given quantities of the gases, there is always a definite composition towards which the mixture tends to approach, and when that composition is reached no further reaction will take place if the temperature be kept constant. In general it may be said that a mixture of either carbon dioxide and hydrogen, or carbon monoxide and steam, at any temperature which occurs in the practical working of a gas producer, will undergo a chemical change resulting in the formation of a mixture of all four gases, in proportions which can be calculated if the conditions are known.

We have given above certain calculations for the theoretical composition of producer gas when the process is carried out without loss of heat, and before leaving this part of the subject we must inquire whether the reactions which may take place between carbon monoxide and steam, or between carbon dioxide and hydrogen, would modify the conclusions which have been arrived at.

In the first case—in which the steam was assumed to be decomposed with the formation of carbon monoxide and hydrogen—the gas does not contain either of the pairs of substances which can interact, for if the hot gas leaving the producer consists only of hydrogen, carbon monoxide, and nitrogen, no further change will take place. In the producer itself, however, there is a mixture of carbon monoxide and steam, and if these gases interact heat will be evolved and there will be an excess of sensible heat developed in the producer and not absorbed by an endothermic change, so that the efficiency of the process would be lowered. If it be assumed that more steam is used, in quantity sufficient to replace that which is used up by this reaction, it will be found that all the heat evolved is required to raise the necessary steam, or, in other words, if the H_2O in equations (6*a*) and (6*b*) is assumed to be in the liquid state, there is no heat change in either case. The result of the interaction of carbon monoxide and steam in the producer is therefore simply the replacement of a small proportion of the carbon monoxide in the gas by an equal volume of hydrogen (having almost exactly the same heating value) mixed with its own volume of carbon dioxide. The gas will therefore be richest if this reaction does not take place, and we are justified in considering the figures given on page 12 as representing the richest producer gas which theoretically can be obtained by the action of a mixture of air and steam on carbon when no auxiliary heat is supplied to the producer.

In the second case, in which it was assumed that the steam was decomposed with the formation of carbon dioxide and hydrogen (equation (5)), the gas leaving the producer contains carbon monoxide, hydrogen and carbon dioxide. While hot, a certain proportion of the two gases last mentioned may react to form carbon monoxide and steam. The heat absorbed in this change is almost exactly equal to the heat given up by the condensation of the steam produced, and since it was assumed that all the heat to be obtained by cooling the gas was to be returned to the producer the final thermal effect of this change is again zero. Its result is simply a slight enrichment of the gas, since hydrogen is replaced by an equal volume of carbon monoxide, and carbon dioxide is replaced by steam which is subsequently condensed, so that the percentage of incombustible gases is reduced. We have already pointed out that, under given conditions the reaction $CO_2 + H_2 = CO + H_2O$ will proceed until a certain quantity of steam is formed, and that no further change will then take place. Hence, if a slight excess of steam were used in the production of the gas, the hot gases would contain carbon monoxide, steam, hydrogen and carbon dioxide, and it may be assumed that the quantity of steam may be such that no further change would take place in the composition of the hot gas. This steam would be subsequently condensed when the gas is cooled, and the heat given up would be used in raising an equal quantity of steam which would again pass through the producer. If we suppose that this is actually done the calculation which was made will still hold good, but it should be noted that the producer gas while hot necessarily contains a small proportion of steam and the figures given only represent its composition after cooling.

To what extent the reactions (6*a*) and (6*b*) actually do take place will be discussed later (Chapter III.); for present purposes it is only necessary to show that they need not be taken into account in calculating the theoretical composition of the ideal producer gas.

In the processes which have so far been considered, the gas necessarily contains a considerable proportion of nitrogen derived from the air used for the conversion of carbon to carbon monoxide. If the gases formed by the action of steam on carbon could be kept separate from the products of the action of air on the carbon a producer gas free from nitrogen, and consisting theoretically of carbon monoxide and hydrogen only, could be obtained. This is the principle adopted in the manufacture of "water-gas;" the method used is to blow the fire in the producer alternately with air and steam, the gases obtained during the two processes being kept separate. The object of this process is to obtain a producer gas free from incombustible constituents; the process must therefore be carried out in such a manner that the steam and carbon interact to form hydrogen and carbon monoxide, whilst the formation of carbon dioxide by the reactions—

$$C + 2H_2O = CO_2 + 2H_2$$

and—

$$CO + H_2O = CO_2 + H_2$$

must be prevented as far as possible. The ideal water-gas consists of a mixture of equal volumes of carbon monoxide and hydrogen. The actual process of making this gas is intermittent, and involves various practical difficulties and drawbacks, which are mentioned in Chapter IV. For the present we will consider an ideal case, where the process would be represented by the following reactions:—

During the air-blow—

$$2C + O_2 = 2CO + 58{,}800 \text{ calories},$$

or—

$$C + O_2 = CO_2 + 97{,}600 \text{ calories}.$$

During the steam-blow—

$$C + H_2O = CO + H_2 - 28{,}800 \text{ calories}.$$

Water-gas made in this way would have the following composition:—

Carbon monoxide	50·0	per cent. by volume.
Hydrogen	50·0	„ „
Total . .	100·0	

Its calorific power would be 3065 calories per cubic meter or 344·5 Brit. T.U. per cubic foot.

If the process could be carried out in an ideal manner, without loss of heat (all the sensible heat which is carried away by the hot gases, as well as the heat of combustion of the gas produced during the air-blow and the radiated heat, being returned to the producer by regenerative processes), it would only be necessary during the air-blow to have sufficient carbon to make good the heat absorbed by the reaction between carbon and steam. If the materials used were solid carbon and water at 20° C., then the quantity of heat required for the formation of 44·64 c.m. of water-gas, from 12 kilos of carbon and 18 kilos water, would be 10,800 calories to evaporate the water, and 28,800 calories for the subsequent chemical change, or a total of 39,600 calories. The quantity of carbon which must be burnt to carbon dioxide during the air-blow to supply this heat would be—

$$12 \times \frac{39{,}600}{97{,}600} \text{ or } 12 \times 0{\cdot}406 \text{ kilos.}$$

Thus to produce 1 c.m. of water-gas of the above composition the theoretical quantities of carbon used would be—

$$\frac{12 \times 0{\cdot}406}{44{\cdot}64} = 0{\cdot}109 \text{ kilo during the air-blow,}$$

$$\text{and } \frac{12}{44{\cdot}64} = \underline{0{\cdot}269} \text{ kilo during the steam-blow.}$$

$$\text{Total} \quad . \quad . \quad \underline{0{\cdot}378} \text{ kilo.}$$

One kilo of carbon would, therefore, yield 2·65 c.m. of water-gas.

If during the air-blow the carbon were wholly converted to carbon monoxide, and only the sensible heat of the producer gas so formed were recovered but not its heat of combustion, the amount of carbon required during the air-blow, in order to supply the heat necessary for the subsequent formation of 44·64 c.m. of water-gas, would be—

$$12 \times \frac{39{,}600}{29{,}400} = 12 \times 1{\cdot}347 \text{ kilos.}$$

The quantity of carbon used in the production of 1 c.m. of ideal water-gas, under these conditions, would therefore be—

$$\frac{12 \times 1{\cdot}347}{44{\cdot}64} = 0{\cdot}362 \text{ kilo during the air-blow,}$$

and as before—

$$\underline{0{\cdot}269} \text{ kilo during the steam-blow.}$$

$$\text{Total} \quad . \quad . \quad \underline{0{\cdot}631} \text{ kilo.}$$

One kilo of carbon would therefore yield 1·585 c.m. of water-gas, and in addition it would yield during the air-blow 1·94 c.m. of gas having the composition given on page 6, and a calorific power of 1057 calories per cubic meter.

In actual practice the results are far indeed from these: the reasons for this are mentioned in Chapter IV.

The various cases for which the ideal composition of producer gas has been calculated may be taken as the types of the principal classes of producer gas which are met with in practical work. On the one hand we have the process in which gas is made by the action of an air-blast on solid carbonaceous fuel, and for convenience we will refer to producer gas made in this way as "air-gas."[1] On the other hand there is the gas made by the action of a steam-blast on incandescent fuel, which is universally known as "water-gas;" and intermediate between these two we have gases of varying composition obtained by the action of a mixed blast of air and steam on solid carbonaceous fuel. This last kind of gas is sometimes called "semi-water-gas," or "mixed gas," and apart from ordinary lighting gas it is this type of producer gas which is now almost invariably used for driving gas engines and for heating work. In France producer gas is called "gaz pauvre" and in Germany "generatorgas."

The ideal semi-water-gas, the composition of which is given on p. 12, may be looked upon as a mixture of 2·88 volumes of the ideal air-gas, with 1·48 volumes of the ideal water-gas, as is obvious from the method by which its composition was calculated.[2] The same semi-water-gas would also be produced if the water-gas part of the process were carried out in a theoretically perfect manner, if the carbon monoxide were made without carbon dioxide during the air-blow, and if the alternating air-gas and water-gas thus made were collected in the same gas-holder and there allowed to mix.

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[1] The term "air-gas" is sometimes used to describe a lighting gas made by bubbling air through volatile liquid hydrocarbons, such as gasoline, pentane, etc.; but as this work deals only with producer gas there need be no fear of confusion arising from this source. It may be added that it is undesirable that the name of the inventor of a gas plant should be given to the gas made in his plant, unless it involves some entirely new process for making the gas. The apparatus alone should bear the inventor's name.

[2] Unless otherwise stated, all gas volumes are measured dry at 0° C and 760 mm. pressure. See Appendix B, section 7.

CHAPTER II

THEORY OF PRODUCER GAS (CONTINUED)

In the previous chapter we have shown that the numerous varieties of producer gas may be broadly classified under three heads—air-gas, water-gas, and semi-water-gas—according to the process by which the gas is made. In each case the theory of the process has been considered on the supposition that the fuel used was pure carbon, and calculations have been made to show what should be the theoretical composition of the gas in each case if the process could be carried out without loss of heat and strictly in accordance with the chemical equations which we have given. The results obtained will serve as a standard of comparison with those obtained in practice, somewhat in the way that the thermal efficiency of a heat-engine may be compared with the calculated thermal efficiency of a perfect engine operating under like conditions.

The theoretical results for each of the three types of gas are summarised in Table I. and for each type a parallel column shows results which have actually been obtained in practical working. We propose in this chapter to discuss the various points of difference between the theoretical and practical results, and from a consideration of the causes of these differences to draw some conclusions as to the methods to be adopted in order to secure the highest efficiency in working and the best practical results.

In practical working it is not to be expected that the results obtained will be as good as those which have been shown by calculation to be the best theoretically obtainable, but a comparison of the figures given in Table I. will be instructive, and it will show that the difference is not so great as might have been expected. Moreover, the results given in this table as

TABLE I.—THEORETICAL AND PRACTICAL RESULTS FOR AIR-GAS, WATER-GAS, AND SEMI-WATER-GAS.

	1	2	3	4	5	6	7	8	9	10
	Ideal air-gas— $C + O = CO$ (page 6).	Air-gas made in small Dowson gas plant.	Ideal semi-water-gas— $\left\{\begin{array}{l}C + O = CO\\ C + H_2O = CO + H_2\end{array}\right.$ (page 12).	Semi-water-gas made at Millwall in Dowson gas plant.	Ideal semi-water-gas— $\left\{\begin{array}{l}C + O = CO\\ C + 2H_2O = CO_2 + 2H_2\end{array}\right.$ (page 13).	Semi-water-gas made in Mond gas plant.	Ideal water-gas, when CO_2 is formed during the blow (page 18).	Water-gas made by the Dellwik-Fleischer process.	Ideal water-gas, when CO is formed during the blow (page 18).	Water-gas made at Essen.
Fuel used.	Carbon. 100%	Coke. C, 95% H_2O — Ash, 5%	Carbon. 100%	Anthracite.	Carbon. 100%	Bituminous coal. H_2O, 8·6% Ash, 10·42% Total C, 62·69% Volatile matter (excluding C), 18·29%	Carbon. 100%	Coke. C, 87·56%	Carbon. 100%	Coke. C, 84·8% H, 0·5% Ash, 10·6% H_2O, 2·0% $O_2 + N_2$, 2·1%
Composition of gas (per cent. by volume)—										
Carbon monoxide	34·7%	32·6%	39·9%	27·6%	19·7%	11·0%	50·0%	—	50·0%	44·0%
Hydrogen	—	1·0%	17·0%	15·3%	28·8%	29·0%	50·0%	—	50·0%	48·6%
Methane	—	—	—	1·4%	—	2·0%	—	—	—	0·4%
Carbon dioxide	—	1·4%	—	3·9%	14·4%	16·0%	—	—	—	3·3%
Oxygen	—	—	—	—	—	—	—	—	—	—
Nitrogen	65·3%	65·0%	43·1%	51·8%	37·1%	42·0%	—	—	—	3·7%
Total combustible gases	34·7%	33·6%	56·9%	44·3%	48·5%	42·0%	100%	—	100%	93·0%
Calorific power—										
Calories per cubic meter	1057	1023	1740	1450	1490	1422	3065	2835	3065	2878
British thermal units per cubic foot	118·8	115·0	195·6	163	167·5	160·0	344·5	318·7	344·5	323·5
Calorific intensity (theoretical, see Appendix B)—										
Centigrade degrees	1563	1529	1826	1646	1617	1558	2062	—	2062	2021
Fahrenheit degrees	2845	2784	3319	2995	2943	2836	3744	—	3744	3670
Yield of gas—										
Cubic meters per kilo of fuel	5·36	5·17	4·65	4·37	5·45	3·69	2·65	2·15	1·585	1·13
Cubic feet per ton of fuel	192,000	186,000	167,000	157,000	195,000	132,500	93,000	77,241	57,000	40,500
Thermal efficiency—per cent.	100	—	100	80·6[1]	100	84·1[2]	100	82	—	42[2]
Steam used—kilos per kilo of fuel	—	0·04[3]	0·64	about 0·75	1·29	used, 2·5 decomposed, 0·5	1·07[4]	—	0·64[4]	—
Air used—										
Kilos per kilo of fuel	5·73	5·57	3·29	3·70	3·31	2·53	3·30[4]	—	3·29[4]	—
Cubic meters per cubic meter of gas	0·83	0·83	0·55	0·55	0·47	0·885	0·96	—	1·60	—
Air required for combustion of one cubic meter of gas (cubic meters)	0·83	0·80	1·35	1·15	1·15	1·15	2·38	—	2·38	2·24

[1] Including fuel used for raising steam.

[2] Excluding fuel used for raising steam.

[3] Derived from moisture in atmosphere.

[4] Reckoned in total fuel used.

representing actual practice have not been selected as exceptionally favourable ones; they are presented as examples of what is actually done with well-known types of gas-producer plant in which the processes are used which have been considered theoretically in Chapter I. The figures given in column 2 of Table I. were obtained with a small Dowson gas plant working without steam, the air being forced through the producer by a positive blower; column 4 gives the results obtained from a 250-B.H.P. Dowson plant at the works of Messrs. J. & E. Wright of Millwall[1]; column 6 gives results published by Mr. H. A. Humphrey,[2] and obtained with a Mond plant at the chemical works of Messrs. Brunner, Mond & Co. at Winnington; column 8 is based on the results obtained by Prof. Vivian Lewes, with a Dellwik-Fleischer water-gas plant;[3] and the figures in column 10 represent water-gas made at Essen, and are quoted from Fischer's "Handbuch der chemischen technologie."[4]

One of the principal causes of the differences between the theoretical and the actual results is that the fuels used in practice contain other constituents than carbon, which alone was taken into account in the calculations made in the previous chapter. With the exception of coke and charcoal, all ordinary fuels when subjected to heat give off smaller or greater quantities of volatile substances; and if the temperature be high and the heating sufficiently prolonged the residue of the fuel which is left consists almost entirely of carbon together with the incombustible mineral constituents. In a gas producer working in the ordinary way with an upward draught, as described on p. 3, each fresh charge of fuel is heated and is thus subjected to some extent to this process of distillation before it descends into the zone where partial combustion takes place. The volatile substances which are distilled off then mix with the gas that is being formed according to the chemical changes which have been discussed in the previous chapter. The fuel which takes part in these chemical reactions is not the raw fuel that is put in the producer, but is the residue which

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[1] *Proceedings Inst. C.E.*, 1901, vol. cxliv. p. 269.
[2] *Proceedings Inst. M.E.*, 1901, p. 73.
[3] *Journal Iron and Steel Inst.*, 1900, vol. i. p. 125.
[4] Vol. i. p. 50 (15th German edition).

is left when the raw fuel has been more or less completely deprived of its volatile constituents by the action of heat. The gas actually obtained from such fuel may therefore be regarded as consisting of a producer gas obtained from pure carbon, mixed with the volatile substances given off by the distillation of the fuel. The composition of the gas will depend largely on the nature and amount of these volatile substances. They vary very considerably, as almost all classes of fuels are used, from anthracite, which contains very little volatile matter, to peat, wood, or even sawdust at the other extreme. The volatile constituents of different fuels are discussed more fully in Chapter XII. on fuel, and it will be sufficient for our present purpose to point out that they consist partly of gases and partly of condensable vapours, and that in many cases the latter must be condensed and separated from the producer gas before it can be used. In the case of bituminous or semi-bituminous coals, lignite, peat, and other fuels rich in oxygen and hydrogen, the quantity of tarry matter which is given off on distillation is very considerable and may represent as much as 8 or 9 per cent. of the total heating value of the fuel. When the gas is cooled and scrubbed before use the tar which is separated has little value, and there is thus an unavoidable waste on this account in the use of such fuels in producers where clean cool gas is required. It is therefore an important point in the design of gas producers for use with bituminous fuels to arrange that the tarry vapours may either be burnt in the producer itself, or decomposed and converted to combustible gases which will not condense at ordinary temperatures. This point is further discussed in Chapter IX. on Gas from Bituminous Coal for Engine Work.

Confining our attention to the case of a cool clean gas, to which all the analyses in Table I. refer, the composition of the gas will be affected by the nature of the *gaseous* products of distillation of the fuel. For the air-gas (column 2) and water-gas (columns 8 and 10) the fuel used was ordinary gas-coke; as it had already been strongly heated for a considerable time in retorts there were practically no gases distilled off from it by the action of heat alone in the producer, and the composition of the producer gas obtained from it agrees well with the calculated figures given in columns 1, 7, and 9. The fuels used in the production of the semi-water-gases referred to in columns 4 and 6 were anthracite and bituminous coal respectively, and in these cases the gas formed from the fixed carbon in the fuel was mixed with a certain quantity of other gases given up by the action of heat on the fuel. The following analyses will show the general character of the gases which are given off by the action of heat on fuels of this class:—

Gas evolved on heating Anthracite without Air.

1 kilo of anthracite yielded 0·168 c.m. of gas of the following composition:—

	Per cent. by volume.
Carbon monoxide	4·3
Hydrogen	70·6
Methane	18·9
Carbon dioxide	1·1
Oxygen	—
Nitrogen	5·1
Total	100·0

Gas evolved on heating Bituminous Coal without Air.

1 kilo of coal yielded 0·168 c.m. of gas of the following composition:—

	Per cent. by volume.
Carbon monoxide	13·2
Hydrogen	36·0
Methane	40·9
Carbon dioxide	3·6
Oxygen	—
Nitrogen	6·3
Total	100·0

It will be noticed that anthracite on heating yields both hydrogen and methane, and we should expect that a producer gas made from anthracite would contain a greater proportion of these two constituents than gas made under similar conditions from coke. That this is actually the case is shown by the following analyses of producer gas made from coke and from anthracite respectively in the same producer and under as nearly the same conditions as were practically possible:—

Gas made from Coke.

	Per cent by volume.
Carbon monoxide	22·6
Hydrogen	14·3
Methane	0·75
Carbon dioxide	8·45
Oxygen	0·2
Nitrogen	53·7
Total	100·0

Heating value . 1201 calories per cubic meter.
„ „ . 135 Brit. T.U. per cubic foot.

Gas made from Anthracite.

	Per cent. by volume.
Carbon monoxide	20·1
Hydrogen	19·25
Methane	1·2
Carbon dioxide	9·25
Oxygen	0·15
Nitrogen	50·05
Total	100·0

Heating value . 1326 calories per cubic meter.
„ „ . 149 Brit. T.U. per cubic foot.

The percentage of combustible constituents varies in different samples of fuel, especially with anthracite, and a more exact comparison may be made by taking volumes of the two gases which contain the same weight of carbon. Taking the above analyses as a basis, there will be 100 volumes of gas made from coke and 104 volumes of gas made from anthracite, and they will consist of the following:—

Gas made from Coke.

	Volumes.
Carbon monoxide	22·6
Hydrogen	14·3
Methane	0·75
Carbon dioxide	8·45
Oxygen	0·2
Nitrogen	53·7
Total	100·0

Gas made from Anthracite.

	Volumes.
Carbon monoxide	20·9
Hydrogen	20·05
Methane	1·25
Carbon dioxide	9·6
Oxygen	0·15
Nitrogen	52·05
Total	104·0

The most notable feature in comparing these two sets of figures is the greater proportion of hydrogen and of methane in the gas made from anthracite. In the gas made from coke the hydrogen is formed almost entirely from the decomposition of steam in the producer; the excess of hydrogen in the gas made from anthracite is accounted for by the fact that this fuel contains from two to five per cent. by weight of hydrogen, and a part of this is set free when the anthracite is heated. The superiority of anthracite over coke as fuel for the production of gas of good heating value consists chiefly in the fact that it gives a richer gas, owing to the hydrogen and methane which it yields when heated.

In the same way the effect of the volatile constituents of bituminous fuel is to increase the amounts of hydrogen and methane in the semi-water-gas obtained from it, and this fact must be borne in mind in comparing the figures of column 5 (referring to a gas made from pure carbon) with those of column 6, which represent the composition of a gas made from a bituminous coal. This case, however, is not quite so simple as that of the semi-water-gas made from anthracite, for the Mond producer is so designed that the tarry vapours given off by the distillation of the fuel in the upper part of the producer are partially converted into fixed gases before they enter the scrubbing plant. In this case, therefore, the gas formed from the volatile part of the fuel by the action of heat alone may be very different in composition from the gases obtained by heating a sample of the fuel in a laboratory test. The greater part of this semi-water-gas is, however, formed by the interactions of air, steam, and the fixed carbon in the fuel, so that the comparison of the figures of columns 5 and 6 of Table I. is not without value.

We are now in a better position to understand the difference between the calculated theoretical results and those actually obtained in practice. Comparing columns 1 and 2, the difference is very slight, showing that the chemical reactions have actually taken place almost exactly as was assumed in Chapter I. for a case of this kind. In the two examples of semi-water-gas in Table I. it might have been expected from what has already been said that the proportion of hydrogen in the gases would have exceeded the calculated figures rather than have fallen short of them; as a fact the percentage of hydrogen is only about the same as the calculated value, although it does actually bear a greater ratio to the amount of carbon in the gas than in the theoretical cases. The methane in semi-water-gas is produced, as has already been pointed out, by the action of heat on anthracite or bituminous coal.

We have often found, however, that semi-water-gas made from coke contains a small amount of methane (generally about 0·5 per cent. by volume), and it is therefore interesting to inquire whether this gas can be formed in the producer synthetically, as well as by the decomposition of other hydrocarbons. Bone and Jerdan[1] have shown that at 1200° C. small quantities of methane are formed by the direct union of carbon and hydrogen, and that this is the only hydrocarbon formed. Other compounds of carbon and hydrogen are decomposed at this temperature with the formation of methane, carbon and hydrogen. Further, it is well known that carbon dioxide or carbon monoxide can react with hydrogen, methane being formed, according to the equations—

$$CO_2 + 4H_2 = CH_4 + 2H_2O$$
$$\text{and } CO + 3H_2 = CH_4 + H_2O,$$

but these reactions only take place in the presence of some catalytic agent such as reduced nickel, or under the influence of

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[1] *Journal of the Chemical Society: Proceedings*, 1901, vol. xvii. p. 162; *Transactions*, 1897, vol. lxxi. p. 52.

the electric spark, and Bone and Jerdan showed that no methane was formed by the action of heat alone on a mixture of carbon monoxide and hydrogen.

We may therefore suppose that the methane in producer gas is due chiefly to the decomposition by heat of the volatile constituents of the fuel, but that it may also be formed to some extent by the direct union of carbon and hydrogen when the producer is worked at a high temperature.

As regards the remaining constituents of the semi-water-gas, viz. carbon monoxide, carbon dioxide and nitrogen, the differences are much more marked. Broadly speaking, there are in every case smaller proportions of the combustible gas carbon monoxide, and larger proportions of the incombustible gases carbon dioxide and nitrogen, in the practical results than in the ideal gases. Even in the case of air-gas made from coke, if we leave out of consideration the presence of hydrogen, which is due simply to the decomposition of the moisture present in the air used for the process, the difference between theory and practice is of the character just indicated; in the other examples the differences are somewhat obscured by the fact that a certain quantity of hydrogen, etc., has been added to the gases formed by the chemical reactions on which the theoretical results are based, so that the *percentages* of the other constituents of the producer gas are reduced. To get a better idea of the extent to which the theoretical chemical reactions are followed, we give below the composition of so much of each of the gases in columns 4 and 6 as contain the same amount of carbon as 100 volumes of the corresponding ideal gas.

Ideal Semi-water-gas formed according to the Equations—

$$C + O = CO$$

and $C + H_2O = CO + H_2$

100 vols. (containing 39·9 parts of carbon) consist of—

	Per cent. by volume.
Carbon monoxide	39·9
Hydrogen	17·0
Methane	—
Carbon dioxide	—
Nitrogen	43·1
Total	100·0

Semi-water-gas made at Millwall.

121·3 vols. (containing the same amount of carbon) consist of—.

	Volumes.
Carbon monoxide	33·5
Hydrogen	18·6
Methane	1·7
Carbon dioxide	4·7
Nitrogen	62·8
Total	121·3

Semi-water-gas formed according to the Equations—
$C + O = CO$
and $C + 2H_2O = CO_2 + 2H_2$

100 vols. (containing 34·1 parts of carbon) consist of—

	Per cent. by volume.
Carbon monoxide	19·7
Hydrogen	28·8
Methane	—
Carbon dioxide	14·4
Nitrogen	37·1
Total	100·0

Semi-water-gas made at Winnington.

117·6 vols. (containing the same amount of carbon) consist of—

	Volumes.
Carbon monoxide	12·9
Hydrogen	34·1
Methane	2·4
Carbon dioxide	18·8
Nitrogen	49·4
Total	117·6

For producer gas made from anthracite or bituminous coal it would be impossible to give an exact comparison between theory and practice, unless the composition of the distillation gases and also their volume in relation to the amount of fixed carbon in the fuel were accurately known. Nevertheless, it is clear from the above figures that so far as the reactions between air, steam, and carbon are concerned, the departures from theory are in the direction indicated, viz. that there is in practical working an amount of carbon dioxide considerably greater than that shown by theory, while the proportion of carbon monoxide is considerably less. Remembering that the semi-water-gas of columns 4 and 6 may be considered as true semi-water-gas (formed from steam, air, and carbon) diluted with distillation gases containing little, if any, carbon dioxide or nitrogen, we should expect to find the percentages of the two latter gases less, rather than greater, in practice than in theory. Since the reverse is actually the case, we should find, if we could distinguish the distillation gases from the producer gas (which together make up the semi-water-gas), considerably higher proportions of carbon dioxide and nitrogen in the producer-gas portion than is indicated by theory.

In part this is due to the fact that the heat of combustion of the carbon cannot be completely utilised, while the calculations for semi-water-gas in Chapter I. were based on the assumption that no heat losses took place. Certain sources of heat loss are always present, although by suitable design they can be minimised. For example, radiation from the gas producer and from the pipes conveying hot gases is unavoidable; but it is not unusual to recover a portion of this heat by having an outer casing round the producer and outlet pipes, the air-supply for the producer being drawn through this casing and being heated before it reaches the fire. The principal heat loss is, however, in the large quantity carried away by the gas as it leaves the producer; and a considerable proportion of this heat may be utilised in raising the steam required for making the gas, by passing the hot gas through a tubular boiler or other suitable contrivance. In practice the gas must leave the last-named apparatus at a temperature considerably above that of the steam which is produced, so that only a portion of the sensible heat of the gases is recovered; moreover, as the gases are cooled it becomes more difficult to make use of their sensible heat, and a point is soon reached at which it is no longer useful to increase the cost of the plant for the sake of a slightly increased economy of heat. Thus in practice, when the gas is to be used cold, it is necessary to abstract the remaining sensible heat of the gas without making use of the heat withdrawn. Usually this is done by transferring the heat to a supply of cold water which is mixed intimately with the gas. There is one notable exception in which the hot water obtained from the cooling tower is used to heat the air-supply for the producer and to saturate it with vapour; but even in this case the recovery of heat is necessarily far from complete.

If the fuel used is moist there is a further loss, because heat is required to evaporate the moisture. In a simple producer worked with an up-draught and with the fuel introduced at the top, as in Fig. 2, the moisture is evaporated and passes away with the gas, and is subsequently condensed when the gas is cooled. Ordinarily the loss is but small; for example, in the case of anthracite containing 5 per cent. of moisture, a figure rather above than below the average, only about 0·3 per cent. of the heat of combustion of the fuel would be lost in evaporating the moisture which it contains. In some cases, however, the effect of moisture in the fuel is more serious. In the case of air-dried peat, for instance, which contains at the least from 20 to 25 per cent. of moisture, and has a heat of combustion only about one-half that of anthracite, the heat used up in evaporating the moisture would be about 3 per cent. of the total heat of combustion of the fuel.

The final result of all such heat losses is that the reactions which require heat, viz.—

$$C + H_2O = CO + H_2 - 28{,}800 \text{ calories,}$$
$$\text{and } C + 2H_2O = CO_2 + 2H_2 - 18{,}800 \text{ calories,}$$

cannot take place to the fullest extent, so that the gas formed by the action of air and steam on the fixed carbon of the fuel contains less hydrogen and more nitrogen than the ideal gas. Where the steam is decomposed with formation of carbon dioxide and hydrogen we should therefore expect to find less carbon dioxide in the actual gas, since the formation of this constituent by the reaction between steam and carbon is hindered equally with the formation of hydrogen. Actually, however, the percentage of carbon dioxide is considerably greater in this case than the calculated number, pointing to the fact that some considerable portion of the carbon dioxide produced by the reaction—

$$C + O_2 = CO_2 + 97{,}600 \text{ calories,}$$

escapes the subsequent change to carbon monoxide. This is, in fact, one of the most important points in which the practical results differ from the theoretical, and it is worth while to consider the consequences to which it may lead.

Regarded from the standpoint of thermal efficiency, the effect of the combination of carbon in the producer with the oxygen of the air to form carbon dioxide without subsequent reduction to carbon monoxide would be to render more heat available for the reactions between steam and carbon in which heat is absorbed. Theoretically, therefore, a greater quantity of steam could be decomposed than is possible when carbon monoxide is the sole product of the reaction between carbon and atmospheric oxygen. By following the method used in the previous chapter we can calculate what would be the composition of a producer gas formed in this way, assuming the absence of heat losses. Two cases are possible, because the reaction between steam and carbon may take place in two ways; but it may be said at once that under the conditions which are necessary to bring about the change expressed by the equation—

$$H_2O + C = H_2 + CO - 28{,}800 \text{ calories,}$$

the action of air on carbon leads to the formation of carbon monoxide accompanied by a comparatively small amount of carbon dioxide.[1] Hence we need only consider the alternative case, viz. that of a producer gas formed (without heat loss) by the reactions—

$$C + O_2 = CO_2 + 97{,}600 \text{ calories,}$$
$$2H_2O + C = 2H_2 + CO_2 - 18{,}800 \text{ calories.}$$

We do not suggest that it is possible for a producer gas to approximate very closely to this assumed case. It has already been shown that in practice, when the steam and carbon interact in accordance with the second of these two equations, the air and carbon interact so as to form both carbon monoxide and carbon dioxide. We do not know the relative amount of these two gases formed by the reaction between air and carbon in this case, but by assuming that the union of carbon and atmospheric oxygen in the producer leads to the formation of the dioxide only we shall get the extreme result; and we can also calculate the theoretical results for some assumed intermediate cases.

For every 12 kilos of carbon which combine with oxygen, in accordance with equation (1) in Chapter I., one volume (22·32 c.m.) of carbon dioxide is formed and 97,600 calories are liberated. According to equation (5), the interaction of 36 kilos of steam with 12 kilos of carbon gives rise to the formation of two volumes of hydrogen and one volume of carbon dioxide, and 18,800 calories are absorbed. To this we must add the latent heat of the steam, viz. 21,600 calories (see p. 11), so that the heat which must be supplied is 18,800 + 21,600 = 40,400 calories. If all the heat liberated in the combustion of 12 kilos carbon be used up in the decomposition of steam by a further quantity of carbon, the quantity of steam decomposed will be—

$$36 \times \frac{97{,}600}{40{,}400} \text{ or } 36 \times 2{\cdot}416 \text{ kilos.}$$

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[1] See Chapter III. pp. 50 and 57.

The gas will, therefore, consist of—

Carbon dioxide	1·00	vol. containing 12 kilos of carbon	From air and carbon.
Nitrogen	3·76	vols.	
Carbon dioxide	2·416	vols. containing 12 × 2·416 = 28·99 kilos carbon	From steam and carbon.
Hydrogen	4·83	vols.	
Total	12·00	vols. containing 40·99 kilos carbon.	

The quantity of steam used is $\frac{36 \times 2{\cdot}416}{40{\cdot}99}$, or 2·12 kilos per kilo of carbon.

The composition of this gas by volume will be as follows:—

Carbon dioxide	28·45 per cent.
Hydrogen	40·25 ,,
Nitrogen	31·30 ,,
Total	100·00

Its heating value will be 1243 calories per cubic meter, or 139·7 Brit. T.U. per cubic foot; and the yield of gas will be 12·01 × 22·32 c.m. from 40·99 kilos of carbon, or 6·54 cubic meters per kilo of carbon.

It will thus be seen that the gas formed in this way is weaker than that referred to in column 5 of Table I., although there is a correspondingly greater volume of gas from each kilo of carbon consumed, as we have assumed an entire absence of heat losses.

We have now dealt with the two extreme cases; we have assumed that the reaction between carbon and air gives rise in the one to carbon monoxide, and in the other to carbon dioxide.

It is easy to calculate the theoretical results when different proportions of carbon monoxide and dioxide are produced from air and carbon, and this has been done for several cases. The results are given in Table II., and are shown graphically by the curves of Figs. 3 and 4. In these diagrams the horizontal axis is divided into 100 parts, and the ordinates representing the theoretical composition, etc., of the gas in any particular case are set up against an abscissa which represents the proportion of carbon monoxide in the assumed mixture of carbon monoxide and dioxide formed by the action of atmospheric oxygen on the carbon. Thus,

Table II.—Theoretical Composition of Semi-water-gas when Different Proportions of CO_2 and CO are formed by the Action of Air on Carbon.

Reaction between air and carbon : Proportions of CO and CO_2 formed per cent. by volume.		Composition of semi-water-gas per cent. by volume.				Steam used per kilo of carbon.	Gas formed per kilo of carbon.	Calorific power of gas.	
CO	CO_2	CO_2	CO	H_2	N_2	Kilos.	Cubic meters.	Calories per cubic meter.	Brit. T.U. per cubic foot.
—	100	28·45	—	40·25	31·3	2·12	6·54	1243	139·7
10	90	27·8	0·9	39·7	31·6	2·08	6·48	1254	140·9
20	80	27·1	1·9	39·15	31·85	2·02	6·41	1267	142·4
30	70	26·3	3·0	38·5	32·2	1·97	6·34	1282	144·0
40	60	25·35	4·3	37·7	32·65	1·91	6·26	1298	145·8
50	50	24·3	5·85	36·8	33·05	1·83	6·17	1316	147·9
60	40	23·0	7·65	35·8	33·55	1·75	6·07	1340	150·5
70	30	21·5	9·8	34·55	34·15	1·66	5·95	1366	153·5.
80	20	19·6	12·4	33·0	35·0	1·55	5·81	1398	157·1
90	10	17·3	15·65	31·1	35·95	1·42	5·65	1438	161·6
100	0	14·4	19·7	28·8	37·1	1·26	5·45	1490	167·5

if under certain conditions of temperature, etc., it is assumed that the reaction between air and carbon will yield 80 per cent. of the monoxide and 20 per cent. of dioxide, the theoretical composition of the semi-water-gas is represented by the ordinates **A B** in Figs. 3 and 4. In Fig. 3 the ordinate at any point is divided up to represent the proportions of carbon monoxide, hydrogen, carbon dioxide and nitrogen in the gas. In Fig. 4, the percentage of each constituent is measured independently from the same horizontal axis, and other data are also given in the same diagram.

It will be seen from these diagrams that as the proportion of carbon dioxide formed by the reaction—

$$C + O_2 = CO_2$$

increases, if the heat liberated is still recovered by the decomposition of steam by the reaction—

$$C + 2H_2O = CO_2 + 2H_2,$$

then the percentages of carbon dioxide and hydrogen in the gas increase and the percentages of carbon monoxide and nitrogen decrease; while the quantity of steam used increases and the heating value of the gas decreases.

Thus, in consequence of the fact that the action of air on carbon may lead to the formation, not of carbon monoxide only as

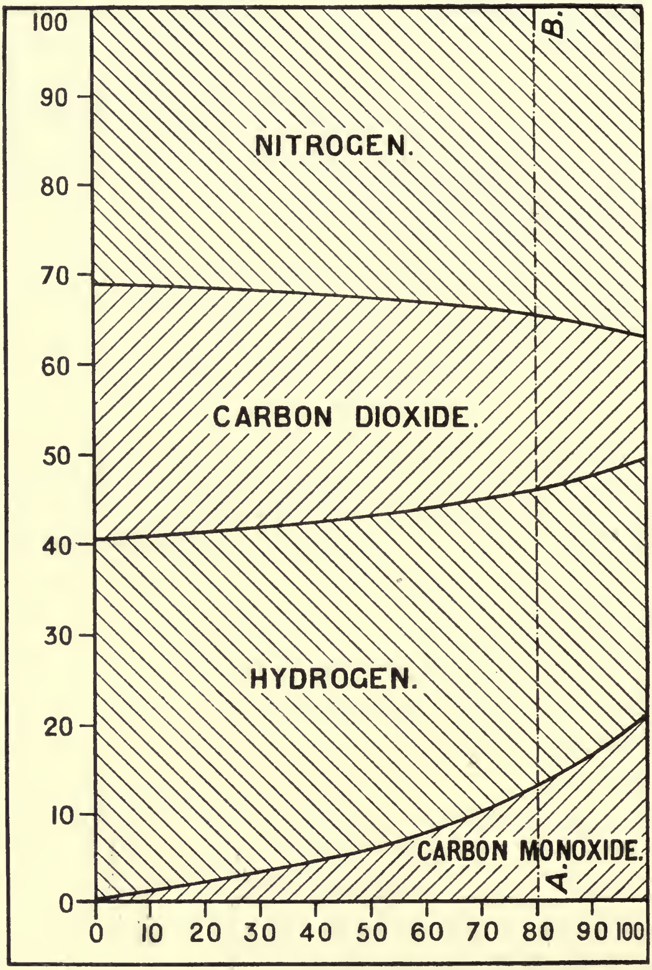

FIG. 3.—Theoretical composition of semi-water-gas, when different proportions of CO and CO_2 are formed by the action of air on carbon.

was assumed in Chapter I., but of a mixture of carbon monoxide and carbon dioxide, the quantity of heat available for the reaction between carbon and steam may be greater, and the theoretical

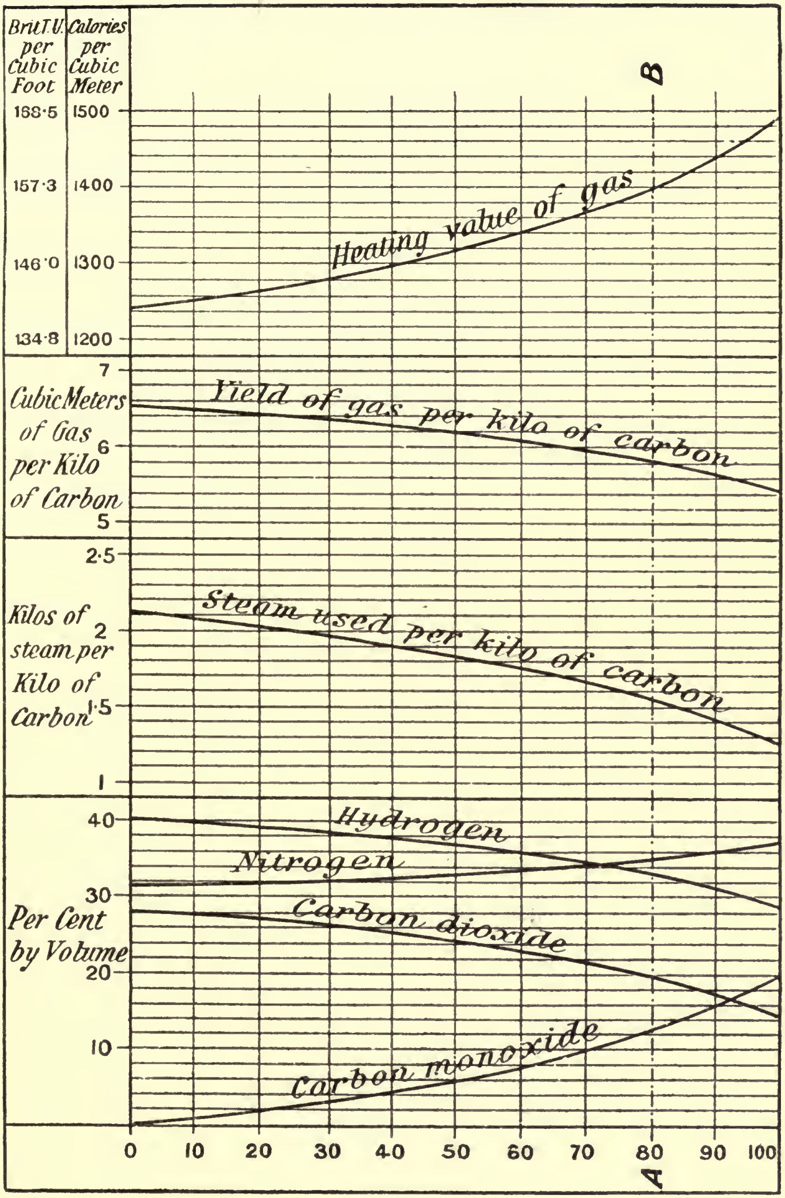

Fig. 4.—Theoretical composition, etc., of semi-water-gas, when different proportions of CO and CO_2 are formed by the action of air on carbon.

composition of semi-water-gas somewhat different from the figures given in Chapter I. As we shall see in the next chapter, a high temperature is required for the reaction—

$$C + H_2O = CO + H_2,$$

and at the same temperature very little carbon dioxide is formed by the action of air on carbon, the change being practically that represented by the equation—

$$C + O = CO.$$

The figures based on these two reactions and summarised in column 3 of Table I. may therefore be taken as a standard of comparison for semi-water-gas made at a high temperature.

When working with excess of steam and with a low temperature, as in the Mond plant, the actual results obtained show that the action of air on carbon leads to the formation of carbon dioxide as well as carbon monoxide, and we shall see in Chapter III. that this is a necessary consequence of a low temperature. It must therefore be understood that it is impossible to realise the results of column 5, Table I., since under the conditions required for the reaction—

$$C + 2H_2O = CO_2 + 2H_2$$

the interaction of air and carbon must give carbon dioxide as well as carbon monoxide. The effect which this has on the theoretical composition of the gas is shown in Figs. 3 and 4. If the heat efficiency of the process is maintained at 100 per cent., then at lower working temperatures more CO_2 will be formed from air and carbon, the theoretical proportions of CO_2 and hydrogen in the gas will be greater, and that of carbon monoxide will be less, while the calorific power of the gas will also be less.

The difference between the practical results obtained in gas producers and the results which should be obtained theoretically when no heat is wasted are thus seen to be due principally to three causes. Firstly, the fuel used is not pure carbon but contains volatile constituents which mix with the gas and enrich it; secondly, in actual practice a considerable proportion of the heat of the fuel is lost in the process of converting the solid fuel into cool clean gas—and consequently in the cases of semi-water-gas and water-gas the amount of heat available for decomposition of steam is less than the theoretical quantity, so that either the calorific power of the gas or the yield of gas per kilo of fuel (or both of these) is less than should theoretically be the case; and, finally, the theoretical composition of the gas is not attained because the reactions do not take place completely in accordance with the assumed equations.

The principle that the sensible heat of the gas should be recovered as completely as possible and returned to the producer needs no further emphasis. Means for accomplishing this end are provided in some of the principal types of gas-producer plants, and the production of the steam by the sensible heat of the producer gas is a typical feature of most modern suction plants. We shall proceed in the next chapter to study the chemical reactions, with the object of showing what are the conditions which must be observed in order that they may take place in the manner we have assumed in Chapter I.

CHAPTER III

THEORY OF PRODUCER GAS (CONTINUED)

It has already been mentioned that to obtain a combustible gas there must be a considerable depth of fuel in the producer. The passage of a current of air through a thin layer of fuel leads to complete combustion of the fuel, and the hot gases which leave such a fire consist of carbon dioxide mixed with the nitrogen of the air used for the combustion of the fuel, together with a large excess of unburnt air. With a thicker layer of fuel, the amount of air mixed with the products of combustion is less, and there may be a small proportion of carbon monoxide present. With the fuel bed deeper still a combustible gas is obtained which is free from air and contains a fair proportion of carbon monoxide; within limits, the proportion of carbon monoxide can be increased and that of carbon dioxide decreased by increasing the depth of the bed of fuel. This has the double effect of increasing the surface of hot carbon with which the gas comes into contact during its passage through the fire, and of increasing the time during which the reacting substances are in contact with one another.

With the air blast passing at a given velocity through the fire, if the depth of fuel be increased a point will soon be reached at which a further increase has no effect on the proportion of carbon monoxide in the gas; and in practice, in any given case, the depth of fuel should not be much greater than this.

No definite rule can be given as to the depth of fuel required to get the maximum proportion of carbon monoxide, as this will depend on the velocity of the blast and on the size and physical condition of the fuel. The influence of these factors is well illustrated by some experiments carried out by M. Boudouard.[1]

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[1] *Annales de Chimie et de Physique*, 1901, series vii. vol. 24, pp. 5–85.

A certain quantity of carbon dioxide was confined in a porcelain tube in the presence of carbon, and the tube and its contents were kept at a known temperature for a certain time. At the end of the experiment the gases were removed from the tube and analysed, the amount of carbon monoxide formed under known conditions being thus ascertained. In this way Boudouard was able to vary only one condition at a time, and thus obtained some valuable results as to the effects produced by different conditions. We cannot here give all his experimental results, but will quote sufficient to illustrate the conclusions at which he arrived.

To study the influence of the physical condition of the fuel, parallel experiments were made in the manner just described, using wood charcoal, gas carbon, and coke respectively in three separate tubes. A fourth experiment was made with some finely divided carbon prepared by a chemical process. In each case the porcelain tube containing carbon and carbon dioxide was heated to 800° C. for 8 minutes, and the gas in the tube was then analysed. The results obtained were as follows:—

	Per cent. by volume.	
	Carbon dioxide.	Carbon monoxide.
Finely divided carbon	13·6	86·4
Wood charcoal, in pieces 2 to 5 mm. cube .	39·9	60·1
Coke ,, ,, ,,	79·1	20·9
Gas carbon ,, ,, ,,	80·1	19·9

It will be seen that in no case is the conversion of the carbon dioxide to monoxide complete; the change proceeded furthest with the finely divided carbon and nearly as far with wood charcoal. With coke and with gas carbon comparatively little carbon monoxide was formed. These results clearly show that the reaction—

$$CO_2 + C = 2CO$$

proceeds most rapidly if the carbon is in a highly porous condition. In a gas producer the reacting gases are in contact with the hot fuel for a very short time (probably not more than one second), it is, therefore, all important that the chemical changes shall take place as rapidly as possible. Although the time allowed in the experiments quoted was as much as 8 minutes, it should be remembered that there was no movement of the gases through the carbon such as would be the case in a producer, and it is a fair inference that, other things being equal, the percentage of carbon monoxide obtained in a gas producer would be higher if the fuel were of a porous nature than it would be if the fuel were dense and exposed little surface to the gas. From this point of view, wood charcoal would be almost an ideal fuel for use in a gas producer.

The influence of the size of the fuel is shown by experiments similar to the above, but the carbon in its various forms was used in larger pieces (described as of the size of a hazel-nut, *noisette*). The following results were obtained, the tube being heated for 8 minutes at 800° C.:—

	Percentage by volume.	
	Carbon dioxide.	Carbon monoxide.
Wood charcoal, 2 mm. to 5 mm.	39·9	60·1
„ „ size of a nut	17·1	82·9
Coke, 2 mm. to 5 mm.	79·1	20·9
„ size of a nut	83·6	16·4
Gas carbon, 2 mm. to 5 mm.	80·1	19·9
„ size of a nut	86·7	13·3

With coke and gas-carbon, both comparatively non-porous materials, the change proceeded more rapidly with the smaller pieces than with the larger. With wood charcoal the reverse was the case, and this is probably due to the fact that the highly porous character of this fuel masked the influence of so small a variation in the size of the pieces used. In gas producers the fuels used in practice resemble coke or gas-carbon rather than wood charcoal, and it is easy to understand why the reaction should proceed more rapidly with the smaller pieces. A larger surface of hot carbon is exposed to the action of the gases passing through the producer, and the interstices between the separate pieces of fuel are smaller, so that the gas is brought into more intimate contact with the hot carbon. It is clearly of importance both for the conversion of carbon dioxide to monoxide and for the decomposition of the steam, that the fuel should be used in as small pieces as possible. In practice the limit of size is determined by the consideration that the smaller the fuel the greater is the back pressure against the blast; and, further, there is always a certain loss of fuel due to unburnt carbon which is mixed with the ash, and if the producer be one in which some form of grate is used to support the fire and to distribute the air evenly through it the loss of fuel with the ash is greater with the smaller fuel. A small fuel generally contains a good deal of the dust or powder formed in crushing it, and when such fuel is used the quantity of dust carried away by the current of gas may be a serious trouble, leading to fouling of the gas mains, and requiring suitable scrubbing plant to remove it from the gas if the latter is to be used in engines or small burners.

Another factor which can be controlled, and which affects the results obtained, is the sectional area of the producer fire in relation to the rate at which gas is being made, or, in other words, the velocity of the blast through the fire. To illustrate the importance of this, we again quote some experimental results obtained by Boudouard. A porcelain tube, 3 cms. in diameter and 27 cms. long, was packed with pieces of coke about 5 mm. in diameter, and the tube and its contents were placed in a furnace the temperature of which was kept at 800° C. A current of air was passed through the heated column of coke at different rates, and in each case the proportions of carbon monoxide and dioxide in the gas issuing from the tube were determined by analysis. The following are the results obtained:—

Table III.—Effect of Velocity of Air-currents through Heated Carbon.

No. of experiment.	Velocity of air. Liters per minute.	Percentage by volume in issuing gas.		Proportion of carbon converted to—	
		CO_2	CO	CO_2	CO
1	0·10	18·20	5·20	77·8	22·2
2	0·27	18·43	3·80	82·9	17·1
3	1·30	18·92	1·88	91·0	9·0
4	1·465	19·90	1·83	91·6	8·4
5	3·20	19·40	0·93	95·4	4·6

It will be seen that the more rapid the current of air the greater the proportion of carbon dioxide, and the less that of carbon monoxide, formed by the interaction of air with carbon. In a gas producer the currents of air or of air and steam are relatively much slower than in these experiments, but it is apparent that, all other things being equal, the completion of the reactions in a producer is favoured by a slow draught: the time during which the gases and the hot carbon are in contact is thereby increased.

It may be added that all that has been said as to the influence of the various conditions mentioned in the reactions between air and carbon may also be taken to apply generally to the reactions in which steam takes part.

The four conditions which have been mentioned—depth of fuel, porosity of the fuel, the size of the pieces used, and the velocity of the blast—are all interdependent; for example, the depth of fuel required to give the best results will depend on the nature of the fuel, its size, and the velocity of the air-blast. In any given practical case the depth of fuel and the velocity of air-blast must be arranged to suit the character of the fuel which is to be employed. From the general considerations we have already discussed it is obviously desirable that the velocity of the blast should not be excessive. In other words, the producer should have a sectional area large enough for a given rate of gas production; the depth of fuel to be used will then be determined from a consideration of the nature of the fuel and the velocity of the blast. So far we have seen no reason why this principle should not be carried to any extent; in practice, however, the important question of the temperature attained in the producer comes into play, and has a direct bearing on the design of the producer. For reasons which will be explained presently it is necessary to maintain the fuel at a relatively high temperature, therefore the velocity of the blast through the fire cannot be reduced below a certain limit in any given case. On the other hand, if the velocity of the blast be too high' in order to keep up the temperature practical difficulties may arise from the formation of hard clinkers adhering to the firebrick lining of the producer. The designer of a gas producer has therefore to provide for as high a velocity of blast as can safely be allowed without incurring these disadvantages. Several devices have been patented which have for their object the prevention of clinkers, and a few are met with in actual practice, but all will be ineffective unless the dimensions of the producer in relation to its output, and the proportion of steam to air, are such that the temperature attained is not excessive.

We now have to consider the influence of the temperature on the reactions. This is of importance in two ways: the temperature of the reacting substances may affect the velocity with which the change takes place; and it may also affect the final result of the reaction either as to the nature of the substances formed, or as to the quantities in which the reacting substances and the products formed from them are present together when no further change takes place. Like most chemical changes, those with which we are concerned take place most quickly at high temperatures, the velocity of the change increasing very rapidly with a rise of temperature. We may again quote some of Boudouard's experimental results to illustrate this in the case of the conversion of carbon dioxide to carbon monoxide by interaction with carbon. As before, the experiments consisted in heating a known volume of carbon dioxide with carbon in a porcelain tube at a definite temperature, but in this case two separate sets of experiments were made, one at 650° C., the other at 800° C. In each set of experiments tubes were heated for different lengths of time and the proportions of carbon dioxide and carbon monoxide were then determined, so that the progress of the change could be observed. Using carbon in the form of wood charcoal, the following results were obtained:—

Table IV.—Influence of Temperature on the Conversion of CO_2 to CO.

Time.	At 650° C.		Time.	At 800° C.	
	CO_2 per cent.	CO per cent.		CO_2 per cent.	CO per cent.
0 minutes	100·0	—	0 minutes	100·0	—
8 „	81·8	18·2	8 „	17·1	82·9
64 „	71·7	28·3	1 hour	6·1	93·9
6 hours	65·2	34·8	6 hours	6·7	93·3
8 „	63·1	36·9			
9 „	62·4	37·6			
12 „	61·5	38·5			

These results are represented diagrammatically in Fig. 5, in which the horizontal scale gives the number of hours during which the tube has been heated, while the percentage of carbon dioxide remaining unchanged at the end of any time is shown by the vertical height of the curve above the time axis. Curves are drawn in this way to represent the result of each set of experiments, and they show very clearly how much more rapidly the conversion of carbon dioxide to carbon monoxide takes place at the higher temperature.

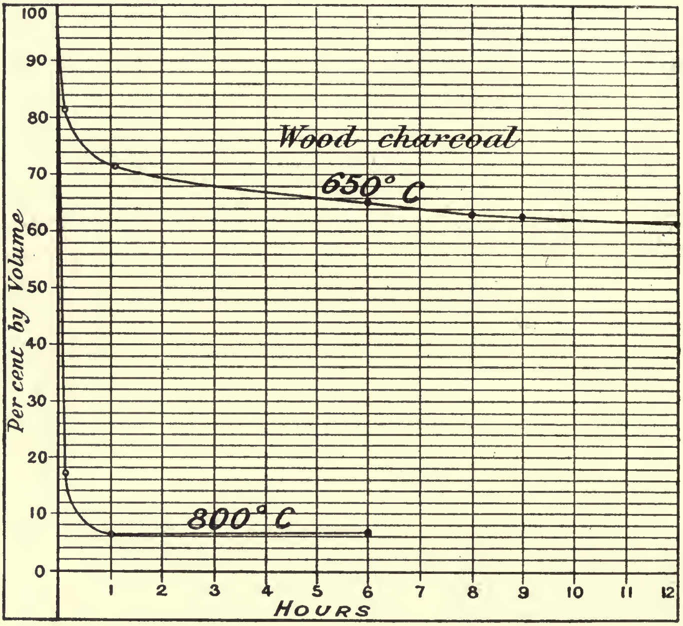

FIG. 5.—Influence of temperature on the conversion of CO_2 to CO.

In a gas producer, as has already been pointed out, the gases are in contact with the fuel for only a very brief period of time, and it is important that the velocity of the reactions should be great in order that the changes may be as complete as possible. The experiments just referred to show one reason why much better results would be expected from a gas producer in which the temperature of the fuel was 800° C. than from one in which the temperature was only 650° C. (if so low a temperature could be used at all). In practice, however, the temperature may be over 1000° C., and similar experiments to those quoted could not easily be carried out owing to the practical difficulties of making accurate experiments with gases at such high temperatures. But the fact that the change proceeds so much more rapidly at 800° C. than at 650° C. makes it reasonable to suppose that at still higher temperatures, such as 1000° C., the conversion of carbon dioxide to carbon monoxide would be practically complete, even in the short time occupied by the gas in passing through the producer.

Before leaving the question of the effect of temperature on the velocity of the reactions, it may be well to point out that this effect will be of the same nature whatever be the size or physical condition of the fuel used. Thus the experiments quoted refer to the interaction of carbon dioxide with wood charcoal—a form of carbon which is very reactive owing to its great porosity. It is equally true that a high temperature is necessary in order that the change may take place with sufficient rapidity when we are dealing with such fuels as are used in practice. Indeed, with these comparatively non-porous fuels, such as anthracite, coke, or bituminous coal, a higher temperature would be required to give as good results as could be obtained with wood charcoal. In Fig. 6 we show in diagram form some results obtained by Boudouard with coke at 800° C. These experiments were made in exactly the same way as the experiments with wood charcoal, represented in Fig. 5; and for the purpose of comparison, we have reproduced in Fig. 6 the curve for wood charcoal at 800° C. in Fig. 5. It will be seen that at the same temperature the change is much slower with coke, and that after only a few minutes' heating the change may be nearly complete with wood charcoal, while it is only beginning to show itself with coke.

A comparison of the curves for wood charcoal at 650° C. and at 800° C. (Fig. 5) will suggest that with coke at a still higher temperature than 800° C. the initial part of the curve would be much steeper, so that the change would be well advanced during the first few minutes.

We may suppose, therefore, that with any given fuel the conditions may be such that the change takes place with sufficient rapidity to ensure its practical completion in the producer. It does not necessarily follow, however, that the carbon dioxide will be completely converted to carbon monoxide. In this respect the reaction we are now considering resembles that referred to on p. 14 (Chapter I.), for at any given temperature there is always a certain proportion of the reacting substances left unchanged, however long they are kept in contact with one another. The experiments already quoted show that at 650° C. the final result of the interaction of carbon and carbon dioxide is the production of a gaseous mixture containing 61·5 volumes of carbon dioxide and 38·5 volumes of carbon monoxide; while at 800° C. the composition of the mixed gases in contact with carbon when no further change takes place is 7 volumes of carbon dioxide with 93 volumes of carbon monoxide. Experiments made at 925° C. showed that at that temperature a mixture containing only 4 volumes of carbon dioxide with 96 volumes of carbon monoxide can be obtained.

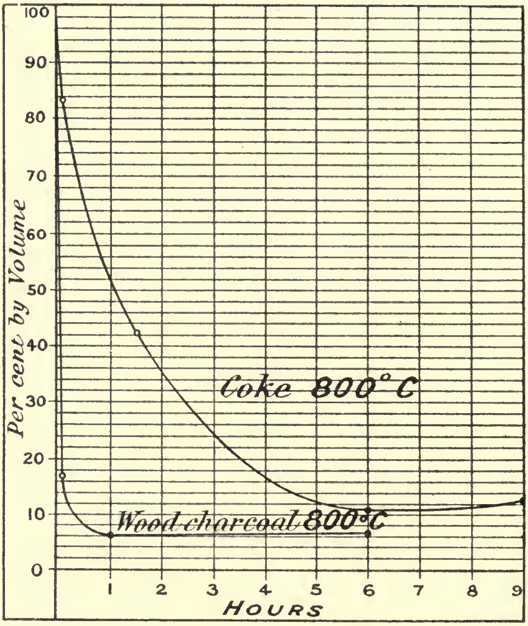

FIG. 6.—Conversion of CO_2 to CO with wood charcoal and with coke at 800° C.

What is of particular importance here is that at any given temperature, however long a time is allowed for the reaction to take place, the change of carbon dioxide to carbon monoxide will be incomplete, and the proportion of carbon dioxide left unchanged cannot be less than has just been stated for those three particular temperatures.

It will also be apparent from these figures that the higher the temperature the smaller is the proportion of carbon dioxide which is left unchanged in the presence of carbon and carbon monoxide.

The reaction between carbon and carbon dioxide is what is called a "reversible reaction;" that is to say, the change may take place in either direction according to the conditions. For example, if a mixture of equal volumes of carbon dioxide and carbon monoxide were heated with carbon at 650° C. in a closed tube, Boudouard's experiments show that change would take place according to the equation—

$$2CO = CO_2 + C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

Heat would be liberated, and the mixture of gases in the tube would consist finally of 61·5 per cent. (by volume) of CO_2, and 38·5 per cent. of carbon monoxide. Supposing, however, that the same mixture of equal volumes of carbon dioxide and monoxide had been heated with carbon at 800° C., the change would have taken place in the reverse sense, according to the equation—

$$CO_2 + C = 2CO \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

Heat would be absorbed, and the mixture of gases would finally have the composition—carbon dioxide 7 per cent., and carbon monoxide 93 per cent. (by volume). The change is therefore reversible, the direction of change depending on the conditions; it is usually considered that the change takes place in both directions simultaneously but that at different temperatures the velocities of the direct and inverse changes are different, so that at low temperatures the reaction (*a*) takes place more rapidly than the reaction (*b*); while at higher temperatures (*b*) takes place more rapidly than (*a*), the result being an apparent reversal of the direction of the reaction as the temperature is increased. It is easy to see from this why at any given temperature there is a definite limit to the proportion of carbon dioxide which can be converted to carbon monoxide. Taking, for example, the temperature of 800° C., if we commence with a tube containing carbon dioxide and carbon these substances will interact and form carbon monoxide. As soon as this is formed the reverse change will commence, and the quantity of carbon monoxide changed back to the dioxide per second will be greater as the amount of carbon monoxide present increases. Similarly, the quantity of carbon dioxide changed to carbon monoxide per second will be less as the amount of carbon dioxide present decreases; so that eventually a state will be reached in which carbon dioxide is being converted to carbon monoxide at the same rate as that at which the reverse change is taking place. There is then no further alteration in the composition of the gas, although the two changes are still going on.

The substances concerned here—carbon, carbon monoxide, and carbon dioxide—are then said to be in equilibrium. At the temperature of 800° C. the reaction—

$$CO_2 + C = 2CO$$

takes place much more rapidly than the reverse change; in other words, the proportion of the molecules of CO_2 which are changed per second to CO is greater than the proportion of molecules of CO which are changed per second to CO_2. The condition of equilibrium is established when equal numbers of molecules are undergoing change in the two ways, and the number of CO_2 molecules present will then be less than the number of CO molecules, the relative amounts of the two gases depending upon the relative velocities of the direct and inverse reactions at this temperature. Since at any temperature the reactions proceed with a definite velocity depending on the temperature it follows that at any temperature there are definite proportions in which the two gases can exist together in the presence of carbon without undergoing further change.

The quantity of solid carbon which is present does not affect the final composition of the gaseous mixture; theoretically it is only necessary that there should be sufficient carbon for the conversion of carbon dioxide to monoxide, although in practice it is necessary to have a large excess of fuel in order that a considerable surface may be exposed to the action of the hot gases, so that the changes may be completed within a reasonable time. Other external conditions besides temperature may affect the proportions in which the substances involved in a reversible chemical change can remain in equilibrium with one another; but so far as the reactions which take place in a gas producer are concerned the only other factor of which it is necessary to speak is the pressure.

The nature of the effect of a change in the external conditions (*i.e.* temperature or pressure) on the final result of a reversible reaction can be deduced from the following general law: "When any system is in chemical equilibrium, a change in one of the factors which determine the equilibrium produces a change in the system, the effect of which is opposite to that of the former change." (Le Chatelier.)

Thus, in the case before us the conversion of carbon dioxide to carbon monoxide is accompanied by an absorption of heat. If, then, we have these substances in equilibrium with one another in the presence of carbon at 800° C., and the temperature be increased, the change which takes place will be one which tends to lower the temperature, *i.e.* more carbon dioxide will be converted to carbon monoxide, this change absorbing heat and so opposing the alteration in temperature. Therefore, the higher the temperature the greater is the proportion of carbon monoxide which can be formed by the action of carbon dioxide upon an excess of carbon.

The effect of a change in pressure can be similarly deduced. Supposing the substances are in equilibrium at a certain temperature and at atmospheric pressure, and that the pressure is increased, then a change in the composition of the gases will take place tending to reduce the pressure. But the conversion of carbon dioxide to carbon monoxide leads to an increase of volume, each volume of carbon dioxide yielding two volumes of the monoxide. Consequently an increase of pressure will disturb the equilibrium, and lead to the formation of a mixture of gases containing more carbon dioxide and less carbon monoxide. The amount of this effect is small.

From the results of the experiment carried out by Boudouard at different temperatures it is possible to calculate the proportions of carbon dioxide and carbon monoxide which can be obtained at any temperature as the final result of the interaction of carbon dioxide and carbon. If the mixture of carbon dioxide and carbon monoxide is always at atmospheric pressure the following are the results calculated from the formula given by Boudouard[1]:—

TABLE V.—PROPORTIONS OF CO_2 AND CO FORMED BY THE ACTION OF OXYGEN ON CARBON AT DIFFERENT TEMPERATURES.

Temperature. Degrees C.	Per cent. by volume.	
	Carbon dioxide.	Carbon monoxide.
446	98	2
495	95	5
538	90	10
588	80	20
623	70	30
651	60	40
678	50	50
703	40	60
731	30	70
747	25	75
764	20	80
786	15	85
814	10	90
834	7·5	92·5
861	5	95
877	4	96
897	3	97
925	2	98
977	1	99
1030	0·5	99·5

---

[1] The formula referred to is—

$$-\frac{21,000}{T} + \log P + \log \frac{c}{c_1^2} = \text{constant}$$

where T = temperature (absolute); P = total pressure of CO and CO_2 in atmospheres; and c and c_1 are the concentrations of CO_2 and CO respectively, *i.e.* the number of gram-molecules in 22·32 liters of the mixed gases. c and c_1 are, therefore, numerically equal to the percentages by volume divided by 100, and in the case considered P = 1, so that log P = 0.

The value of the constant is deduced from three experiments, viz. at 650° C.,

Fig. 7 represents these results diagrammatically; the scale of temperature is taken horizontally, and the vertical height of the curve above the temperature axis represents the percentage of carbon monoxide in the mixture of gases. The vertical distance from the top edge of the diagram down to the curve consequently represents the percentage of carbon dioxide which remains unchanged at any particular temperature.

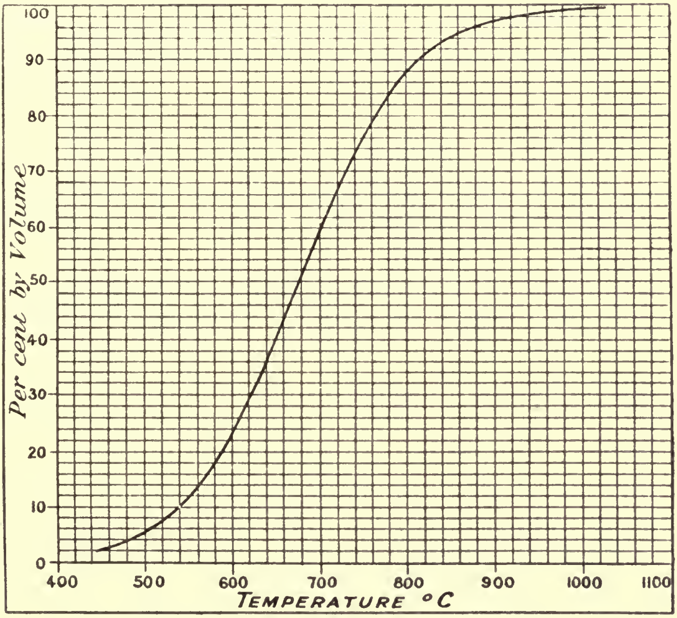

FIG. 7.—Proportions of CO_2 and CO in equilibrium with carbon at different temperatures.

800° C., and 925° C.; the three values obtained are −21·4, −22·2, and −20·6, and the mean value −21·4 is used in the calculations.

We do not think that the value of the constant has been determined with sufficient accuracy to enable us to put forward the results of our calculations as a basis from which to determine the actual temperature which should be attained in a gas producer; but although a small error in the value of the constant would make a considerable difference in the actual value of the temperature corresponding to any particular proportions of CO and CO_2, it would only slightly modify the *shape* of the curves in Figs. 7 and 8. These figures and diagrams will therefore serve our immediate purpose, which is to illustrate the effect of temperature on the equilibrium.

This diagram shows very clearly how important is the influence of a high temperature in increasing the proportion of carbon monoxide which can be obtained from carbon dioxide and carbon; and it also shows that beyond a certain point, which is probably about 1000° C., there is practically no further gain to be derived from increased temperature, so far as the equilibrium is concerned; for at this temperature the reaction does not cease until practically the whole of the carbon dioxide has been converted to carbon monoxide.

In actual practice the gases are largely diluted with nitrogen, so that it is of greater practical interest to consider the final result of the reaction between *air* and carbon at various temperatures.

If the oxygen of the air be first of all completely burnt to carbon dioxide we then have carbon in presence of a gaseous mixture consisting of approximately one volume of carbon dioxide and four volumes of nitrogen, the mixture being at atmospheric pressure. The pressure of the carbon dioxide is therefore only one-fifth of an atmosphere. If the temperature be high, so that the conversion to carbon monoxide is nearly complete, then one volume of carbon dioxide becomes two volumes of carbon monoxide, which is mixed with four volumes of nitrogen. The mixture being at atmospheric pressure, the pressure of the carbon monoxide is one-third of the whole, *i.e.* one-third of an atmosphere. This change in the pressure of the reacting gases as the proportion of dioxide and monoxide alters must be taken into account in calculating the proportions which will represent the final equilibrium at any temperature, and we have calculated in this way (from Boudouard's equation) what would be the final composition of the gases formed from air and carbon at different temperatures when the products of the reaction remain at atmospheric pressure.[1]

These results are given in the following table:—

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[1] See footnote to p. 50.

Table VI.—Composition of Gas formed by the Action of Air on Carbon at Various Temperatures.

Temperature. Degrees C.	Per cent. by volume.		
	Carbon dioxide.	Carbon monoxide.	Nitrogen.
457	19·7	0·5	79·8
494	19·4	1·0	79·6
535	18·8	2·0	79·2
596	17·1	4·9	78·0
651	14·3	9·5	76·2
689	11·6	13·9	74·5
722	9·1	18·2	72·7
753	6·7	22·2	71·1
790	4·3	26·1	69·6
843	2·1	29·8	68·1
907	0·8	31·9	67·3
958	0·4	32·6	67·0
1012	0·2	33·0	66·8

Fig. 8 is drawn in the same way as the preceding diagram to represent these results. The height of the lower curve from the horizontal axis gives the percentage of carbon monoxide in the products formed from air and carbon at any temperature; the vertical distance from the lower to the upper curve gives the percentage of carbon dioxide, and the remainder of the gas is nitrogen. Thus at 800° C., the proportions are—CO 27 per cent., CO_2 3·8 per cent., and N_2 69·2 per cent.

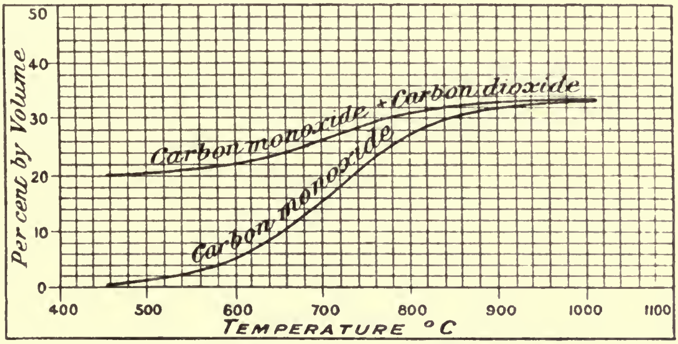

Fig. 8.—Composition of gas formed by the action of air on carbon at various temperatures.

A consideration of these two diagrams (Figs. 7 and 8) will make it clear that a high temperature is necessary, not only that the formation of carbon monoxide may take place quickly enough, but also in order that it may be possible at all to change the greater part of the carbon dioxide into the monoxide. For reasons already explained we do not rely on Boudouard's results to show what temperature should actually be employed, but, judging from our general experience, we agree with his conclusion that the temperature should be about 1000° C. It seems that at this temperature the proportion of carbon dioxide which necessarily remains unchanged is quite small, and the velocity of the change is sufficient to enable it to proceed nearly to its limit in the short time occupied by the passage of the gases through the fuel in the producer.

The foregoing considerations, depending on the fact that the reaction between carbon and carbon dioxide is a reversible one, make it clear that in practice there must always be some proportion of carbon dioxide in producer gas. Not only is it impossible to reduce the proportion of carbon dioxide below, say, one per cent., unless the temperature is above a certain point, but it is also possible for the carbon monoxide to be partially changed back to carbon dioxide and carbon after the gases have left the bed of fuel, in consequence of the reaction—

$$2CO = CO_2 + C.$$

According to Boudouard, this decomposition must be held to explain, to some extent at least, the deposits of soot in the connecting pipes and coolers of a gas-producer plant.

There is, of course, no difficulty in attaining a very high temperature in a generator for the production of air-gas; it is, in fact, customary to add a small proportion of steam to the blast in order to keep down its temperature, in view of the practical difficulties which have to be considered. We are, however, able to refer to an instance in which this expedient was carefully avoided, since it was essential that the gas should contain as little hydrogen as possible. The composition of the gas is given in column 2 of Table I. (p. 21), and it is interesting to note that although the temperature must have been considerably over

1000° C., so that theoretically the gas formed in the producer could have contained very little carbon dioxide, and probably did actually contain only a fraction of one per cent., yet the cooled and scrubbed gas contained as much as 1·4 per cent. of carbon dioxide, which may have been formed by the reaction—

$$2CO = CO_2 + C,$$

occurring during the cooling of the producer gas.

We now come to the consideration of the reactions in which steam takes part. These are three in number, viz.—

$$C + 2H_2O = CO_2 + 2H_2 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$C + H_2O = CO + H_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\text{and } CO + H_2O = CO_2 + H_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The last of these is a reversible reaction (see p. 14, Chapter I.), and should accordingly be written—

$$CO + H_2O \leftrightarrows CO_2 + H_2.$$

The course of the reaction between the steam and carbon depends chiefly upon the temperature. It is found that at low temperatures, *e.g.* 600° C., the products are principally carbon dioxide and hydrogen, *i.e.* the reaction is—

$$C + 2H_2O = CO_2 + 2H_2,$$

although there is, of course, more than sufficient carbon present for the decomposition of the whole of the steam according to the equation (2).

At higher temperatures less carbon dioxide is formed and more carbon monoxide; and at 1000° C. the reaction is very nearly that represented by the equation—

$$C + H_2O = CO + H_2.$$

It will be noticed that the reaction (2) may be regarded as the result of the reactions (1) and (3) occurring together. Thus, if the first product of the action of steam and carbon is a mixture of one volume of carbon dioxide with two volumes of hydrogen, then the carbon dioxide and hydrogen may, under suitable conditions, interact to form carbon monoxide and steam—

$$CO_2 + H_2 = CO + H_2O$$

and if all the carbon dioxide were converted in this way to carbon monoxide half of the hydrogen would be converted back to steam, and the final result would be the production of one volume of carbon monoxide mixed with one volume of hydrogen, as represented in equation (2).

It is not necessary for our present purpose to know whether this double change actually occurs when carbon monoxide and hydrogen are formed from carbon and steam. Whether this be so, or whether the action takes place directly in accordance with the equation (2), the final products will not be carbon monoxide and hydrogen unless the conditions are such as will prevent the formation of carbon dioxide from the interaction of carbon monoxide with steam.

It is therefore important to consider the reversible reaction—

$$CO + H_2O \leftrightarrows CO_2 + H_2$$

from this point of view. The effect of the conditions of temperature and pressure on this reaction may be deduced by exactly the same method as was adopted in considering the reaction $CO_2 + C \leftrightarrows 2CO$ (see p. 49). In this case the change of carbon dioxide and hydrogen to carbon monoxide and steam is attended with absorption of heat; therefore a rise of temperature will increase the proportion of carbon monoxide and steam, and decrease the proportions of carbon dioxide and hydrogen in the mixture of gases which are in equilibrium.[1] We may therefore say that at high temperatures carbon dioxide and hydrogen will react to form carbon monoxide and steam, while at low temperatures the reverse will occur.

Some experiments given by Boudouard show that if a mixture of equal volumes of hydrogen and carbon dioxide be heated, the final composition of the gaseous mixture will be approximately as follows:—

	Per cent. by volume.			
	Carbon dioxide.	Hydrogen.	Carbon monoxide.	Steam.
At 850° C.	35	35	15	15
At 1100° C.	30	30	20	20

---

[1] It may be noted, in passing, that this reaction does not involve any change of volume, and therefore change of pressure has no effect at all on the composition of the mixture of gases in equilibrium with one another at any temperature.

It is clear, therefore, that a very high temperature would be necessary to prevent altogether the formation of carbon dioxide from carbon monoxide and steam. This is a point of great importance in the production of water-gas. This gas is largely manufactured in gas-works and, after being carburetted, it is mixed with the retort gas, and the mixture is distributed for illuminating purposes. The presence of carbon dioxide would be very objectionable, as the illuminating power of the gas would be seriously reduced by it, and it is generally held that the water-gas as it leaves the producers should not contain more than 3 per cent. of carbon dioxide.

In practice it is found that during the steam-blow of a water-gas generator, if the temperature is 1200° C. or over, there is practically no carbon dioxide produced; at 1100° C. carbon dioxide is formed in appreciable quantities; and at 900° C. the amount of carbon dioxide is more than can be considered satisfactory. Also at the lower temperatures part of the steam remains unchanged.

Since the proportion of steam which can remain in equilibrium with carbon monoxide, carbon dioxide, and hydrogen is greater at higher temperatures, the explanation of there being steam left undecomposed when the working temperature is low must be that the velocity of the reactions is not sufficient to secure its complete decomposition. The actual composition of the gas formed by the action of steam on carbon at different temperatures, and the proportion of the steam which is decomposed, have been determined by Dr. Bunte[1] as follows:—

TABLE VII.—ACTION OF STEAM ON CARBON AT VARIOUS TEMPERATURES.

Temperature. Degrees C.	Percentage of steam decomposed.	Composition by volume of gas produced.		
		Hydrogen.	Carbon monoxide.	Carbon dioxide.
674	8·8	65·2	4·9	29·8
758	25·3	65·2	7·8	27·0
838	41·0	61·9	15·1	22·9
954	70·2	53·3	39·3	6·8
1010	94·0	48·8	49·7	1·5
1060	93·0	50·7	48·0	1·3
1125	99·4	50·9	48·5	0·6

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[1] Robinson, "Gas and Petroleum Engines," p. 547.

In a producer for semi-water-gas similar considerations will hold true, but here it is permissible to have considerably more than 3 per cent. of carbon dioxide. When it is desired to obtain a gas of high calorific power it is best that the interaction of steam and carbon should give hydrogen and carbon monoxide, not carbon dioxide; and not only is the percentage of carbon dioxide in the gas reduced by this means, but less steam is used, which in practice means economy in working.

To ensure this condition the temperature should be high, say 1000° C.; this high temperature will also allow any carbon dioxide—formed either from air or pure steam—to react according to the equation—

$$CO_2 + C = 2CO$$

up to the limit corresponding to the temperature, and it will prevent the reaction—

$$CO + H_2O = CO_2 + H_2$$

taking place to a serious extent.

In considering the effect of temperature on the reactions we have spoken of temperatures of 1000° C. and over, and it may be well, therefore, to refer briefly to the question of dissociation, to show that we are justified in the tacit assumption that its effects may be neglected.

It is universally recognised that at high temperatures both carbon dioxide and steam are partially decomposed into simpler substances, but authorities differ as to the temperature at which this effect first becomes appreciable. Mallard and Le Chatelier state that the dissociation of carbon dioxide does not occur below 1800° C., and only amounts to 5 per cent. of the whole at 2000° C.; while steam is not decomposed by heat below 2500° C., and the amount of steam decomposed is very slight at 3300° C. On the other hand, some writers on gas-engines, relying on the early experiments on dissociation by Deville, consider that dissociation takes place between 1000° C. and 1200° C. The question is an important one for the theory of the gas-engine, for temperatures as high as 1850° C. are not uncommon as the result of the explosion in the gas-engine cylinder; but even supposing that dissociation occurs at the lower temperatures mentioned (1000° C. to 1200° C.), it can have very little effect upon the actions in a gas producer, for the dissociation would be only just commencing at the highest temperatures we have considered and its extent would be very slight.

In Chapter I. we have considered the reactions from the point of view of heat efficiency, and it may be well to indicate the bearing upon this of the considerations discussed in the present chapter. It will be remembered that in order to secure the highest possible heat efficiency it is necessary to recover as much as possible of the sensible heat of the gas, and of the heat which would otherwise be lost by radiation from the producer itself, and to utilise the heat so recovered by means of the endothermic reactions in the producer. Now, whether the working temperature of the producer be high or low the waste heat can be at least partially recovered by using it to raise steam for the producer and to heat the air with which the latter is supplied; but the steam obtained cannot be completely decomposed in the producer at a low temperature (see p. 57); and, further, if the temperature be low the endothermic reaction between carbon dioxide and carbon can only occur to a limited extent (see p. 53). The formation of carbon dioxide instead of carbon monoxide does not of itself imply inefficient working, for the extra heat liberated owing to the complete combustion of carbon instead of its partial combustion to carbon monoxide could theoretically be utilised in the decomposition of steam. At a low temperature, however, we have seen that the bulk of the steam will pass unchanged through the producer, and the waste heat used in raising this steam is therefore not really "recovered," so that the producer cannot have a very high efficiency. In the Mond plant a low working temperature is employed for the sake of obtaining ammonia from the nitrogen in the fuel, and it is well known that only one-fifth of the steam used is decomposed. In spite of this, however, the efficiency of the plant is as high as 80 per cent.; but in order to secure this it is necessary to use a large excess of steam so that the small proportion of it which is decomposed is sufficient to absorb the heat evolved in the formation of carbon dioxide and carbon monoxide from air and carbon. A large and expensive plant is therefore necessary to condense the undecomposed steam which accompanies the gas, and to use, as far as is practically possible, the heat which it represents, by heating the air and evaporating the water for use in the producer.

For an ordinary small producer plant such expedients are out of the question, and even if they were adopted the heat efficiency could hardly exceed 80 per cent., whereas by working at a higher temperature a simple apparatus of the type described in Chapter VII. (Fig. 38) may have an efficiency as high as 90 per cent.

In some cases it is necessary for the successful application of producer gas that the gas should be of high calorific power, and this consideration may then be more important than that of heat efficiency and economy of fuel. It will have been gathered from Chapter I. that semi-water-gas will have its highest calorific power if the reactions take place strictly in accordance with the equations—

$$C + O = CO,$$

(or $C + O_2 = CO_2$, followed by $CO_2 + C = 2CO$),

$$\text{and } C + H_2O = CO + H_2,$$

the quantity of steam decomposed being just sufficient to utilise all the heat liberated by the conversion of carbon to carbon monoxide.

In order to approximate to this ideal process it would be necessary that nearly all the sensible heat of the gas and the radiated heat of the producer should be recovered and returned to the producer, and also that the conditions should be such as would enable the reactions to take place in the manner indicated. We have shown in this chapter what these conditions are; for all purposes the conditions dealt with on p. 42 should be observed; and when a rich gas is desired it is specially necessary that the working temperature should be high.

CHAPTER IV

FURNACE WORK

In the previous chapters we have considered the question of producer gas from a theoretical point of view, and in the present and following chapters we propose to deal more especially with its practical applications. To treat the subject in chronological order we will take first furnace and other heating work, as producer gas was first used for this purpose. We will afterwards consider the use of producer gas for driving gas-engines as this is a more modern development.

In considering the use of producer gas for heating work the subject naturally divides itself broadly into two kinds or classes of work, and each should be treated separately. In the first place, there is the heating of furnaces, steam-boilers, drying floors, large evaporating pans, and other apparatus for which it is necessary or desirable to have large flames and to burn the gas in considerable quantities. In such cases it is simplest and best to take hot crude gas direct from the producer to the furnace, without passing it through scrubbers or a gasholder. For such operations it would in fact be a disadvantage to cool and clean the gas, as the condensable hydrocarbon vapours which always accompany gas made from bituminous coal would then be removed. This would not only be wasteful, but the flame temperature in the combustion chamber would be reduced. It is also desirable to take the gas hot from the producer in order that its sensible heat may be used and greater economy effected.

On the other hand, if the gas is to be used in burners or in small jets, and especially if the height of the flames is to be controlled by small cocks so that the heat given off may be constant or varied at will it is essential that the gas should be clean, in order that it may not cause tarry or other troublesome deposits; it is also important that the pressure of the gas at the burners should be steady. This branch of the subject will be dealt with fully in Chapter V.

We have thought it best to emphasise the different conditions under which gas is used for the two kinds or classes of work referred to, and with these broad distinctions in view we will now consider the production of gas for furnaces and similar work. We will also say so much about the application of the gas to its particular work as may be necessary to give a connected idea of the combination of producer and furnace. It would be beyond the scope of this book to describe the many varieties of furnace used for different purposes, and for the same reason we do not attempt to describe the various types of gas-engines. We desire rather to confine ourselves to the theories and principles involved, and to give examples of their practical application, in order to make them understood and appreciated.

In ordinary fires the intention is to burn the solid fuel completely *in situ*, and if any combustible gas passes away unburnt it indicates a defect in the system. On the other hand, the function of a gas producer is to convert the solid fuel into a combustible gas, which can be conveyed far or near to wherever it may be most convenient or desirable to burn it. It is largely a question of convenience, and it must not be supposed that it is in any way possible to add to the heat energy of the fuel from which the gas is derived. We know, from what has been said in Chapter I., that the constituents of the coal or other fuel used can only yield a certain definite amount of heat, which we express in heat units. We cannot add to this amount; we can only endeavour to use the heat to the best advantage. In some cases it is more convenient and more economical to burn the solid fuel in a furnace, and to let the heat obtained pass direct to whatever has to be heated. In other cases it is more convenient and more economical to convert the fuel into producer gas, and afterwards to burn this gas for the purpose of developing heat where it may be required. Necessarily, less heat will be liberated by the combustion of the producer gas than can be obtained by the complete combustion of the solid fuel in a furnace, since, for reasons already explained (Chapter I.), it is not possible in practice to carry out the process of gas-production with its theoretical efficiency of 100 per cent. In ordinary producers, such as are used for furnace work, the heat efficiency seldom exceeds 80 per cent., and is usually less. How, then, we may ask, can it be economical to convert the fuel into gas, if 20 per cent. of its heat energy is lost in the process of making the gas? The answer is not a simple one and involves several explanations, but in the end it will be seen to be satisfactory.

In the first place we know, as a matter of common experience, that when we put coal on a fire there is at once a certain amount of smoke given off, which escapes unburnt and is therefore lost so far as its heating properties are concerned. This smoke consists chiefly of hydrocarbon vapours which are disengaged as soon as the coal is heated; they leave the upper part of the fire at a lower temperature than is necessary for them to burn. The amount of smoke varies with the nature of the coal or other fuel used; it also depends on the condition of the fire when the raw coal is added, on the chimney draught and on other minor considerations. A further considerable loss is due to the heated currents of gas, air, smoke, etc., which are carried up the chimney, commonly known as the convection currents. Theoretically a kilo of average coal requires about 9 c.m. of air for its combustion, but in practice double or treble this quantity of air is often required. The reason is not far to seek: if the fire is not shallow, and if the air-draught is not sufficiently rapid, carbon monoxide will be formed, and there will not be complete combustion of the fuel in the furnace. On the other hand, if there is a shallow fire, and a sufficiently strong draught to ensure complete combustion, there must be a large excess of air drawn in; and as all the nitrogen of the air as well as the oxygen which does not combine with the fuel is heated at the expense of the fuel, it follows that the heat they carry away, as well as that of the products of combustion, is lost. Obviously these heat losses can be reduced if the hot gases and products of combustion can be made to give up some of their heat to the apparatus to be heated, as in the case of a steam-boiler where the heated currents are made to pass through tubes and flues which impart heat to the water in the boiler. But with many furnaces there must not only be a strong draught of air to burn the solid fuel quickly—to get the heat required—but the products of combustion and the accompanying air-currents, when they leave the furnace, pass away up the chimney at a very high temperature, and the loss of heat entailed owing to the large excess of air is very great. Good steam-boilers have a heat efficiency of 70 to 80 per cent., but in some high temperature furnaces fired with solid fuel it is estimated that only 5 to 10 per cent. of the heat value of the fuel is actually used.[1]

There are other losses of heat than those above referred to, principally that of radiation, but for the moment we will suppose that for heating a given furnace or other apparatus the loss from radiation, etc., may be the same with gas as with a solid fire. Let us then consider whether the principal losses we have mentioned would be the same if gas were substituted for solid fuel. In the first place, with gas there need not be any smoke and with reasonable care there should be no unburnt gas to escape up the chimney, it being much more easy to ensure complete combustion with gas than with solid fuel. The gas is not like a solid body, and it is comparatively easy for each molecule of oxygen to come in contact with the molecule of gas with which it is to combine. Usually producer gas requires theoretically about an equal volume of air for its combustion, and in practice little more than this is actually needed. The bearing of this is important and should be appreciated. Theoretically, the coal burnt in a furnace requires a definite amount of air for its complete combustion, and precisely the same total amount of air will be required if the coal is first partially burnt in the producer, and the gas is afterwards burnt to carbon dioxide. But in the latter case practice requires little more air than theory suggests; whereas in the case of direct firing practice requires the theoretical quantity of air to be doubled or even trebled. If, for example, we assume that a kilo of average coal requires theoretically 9 c.m. of air for its combustion we may assume that in practice it will not be necessary to draw into the gas producer and into the gas furnace a total of more than 10 c.m. of air per kilo of coal consumed; but for the fire of a furnace or boiler it will be necessary to draw in say 20 to 30 c.m. of air per kilo of coal burnt. In the latter case, therefore, the amount

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[1] "Ency. Brit.," vol. xxviii. p. 600.

of the flue gases is much greater, and as these gases leave at a high temperature the heat which they carry away with them represents a serious loss.

In the case of a furnace in which the products of combustion leave at a temperature of 800° C. the loss of heat due to this cause will be greater for direct firing than for gas firing by the amount of heat carried away by the extra 20 c.m. of air which are used per kilo of coal, *i.e.* by about 4,900 calories. In other words, when the flue gases leave at this high temperature over 60 per cent. more fuel is required for direct firing than for gas firing, merely to heat the excess of air which is unavoidable in that case. Even where the conditions are most favourable for direct firing, as in the case of a steam-boiler, this loss is not inconsiderable. If the flue gases are cooled to say 200° C., or say 185° above the atmospheric temperature, the heat carried away by 20 c.m. of air will be about 1140 calories, or about one seventh of the total heat of combustion of the fuel.

We have yet to consider another very important saving when gas is used for furnace work; we refer to the fact that when the heated products of combustion leave the furnace proper they can with ease be made to give up the bulk of their heat to the ingoing air required for the combustion of the gas. In this way the air is heated by what would otherwise be waste heat, and this not only reduces the heat losses considerably, but as the air for combustion is highly heated before it meets the gas a much higher temperature can be developed in the furnace. This cannot be done effectually with an ordinary fire, as it would involve a much stronger draught and this increase of draught would increase the excess of air drawn in, with its attendant loss of heat.

For furnace work, if we allow for the absence of smoke, the more complete combustion of fuel in the gaseous form with a much smaller quantity of air than is necessary for solid fuel, and finally, the heating of the air for combustion by the waste heat of the furnace, we shall probably not be wrong in saying that in most cases the heat losses by direct firing may be four or five times as great as by gas firing. On the other hand, we have to allow for a loss of about 20 per cent. of the total heat of the fuel in the process of conversion in the producer; but the net result will show a considerable saving in favour of heating by gas.

Apart from these numerous advantages, there are several other practical considerations which have added greatly to the usefulness of gas for furnace work. For instance, it is a distinct gain in many metallurgical and other operations to maintain a uniform temperature in the furnace, and to be able to raise or lower it as occasion may require. This can be easily accomplished with gas by regulating the gas admission valves, but it is much more difficult and is generally imperfectly done in direct firing with solid fuel. We have also seen that the latter requires a large excess of air, and when the free oxygen of this air comes in contact with metals or other substances having an affinity for it they are more or less oxidised. If producer gas is used there need be no free oxygen, and consequently there need be no oxidation. The gas may even be used to deoxidise the surface of the metal, etc., in the furnace, by the simple expedient of reducing the supply of air to the gas. In this way there is not enough free oxygen to complete the combustion of the gas, and so much of it as is not oxidised seeks oxygen from the oxidised surface of the metal, etc., with which it may come in contact. This is what is known as a "reducing" action. By way of illustration, let us suppose that a plate or bar of iron (free from oxide) is put into a furnace sufficiently heated by an oxidising flame; the surface of the iron will be more or less converted into magnetic iron oxide (Fe_3O_4). But if the iron were coated with rust, or with a scale of iron oxide, and if it were put into a furnace heated by a reducing flame, the gas would attack the iron oxide and take to itself all or part of the oxygen contained in the latter. A further advantage of gas is that it can be conveyed in pipes or flues from one or more producers to one or any number of furnaces wherever they may be situated. For some operations it is also desirable to heat one part of a furnace more than another; in others the heat should be uniform throughout, and all this can be effected more easily and more thoroughly with gas.

The first internally fired gas producer was introduced by Bischof,[1] of Mägdesprung in the Harz, in 1839, and a sectional

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[1] Crookes and Röhrig, "Practical Treatise on Metallurgy," vol. iii. p. 495.

view of it is given in Fig. 9. The theory of its action is similar to that of Fig. 1 (p. 3), the air being drawn in by a chimney draught through the openings **AA**, and through the firebars **B**, the fuel being introduced at **C**, and the gas escaping at the outlet **D**. Since then there have been numerous modifications and new departures in this country and in others, but many of them have a mere historical interest, and we propose to select only such as may help our readers to appreciate the developments and improvements which have occurred. Those who wish to trace the growth of the subject historically cannot do better than consult the paper of Mr. F. J. Rowan on "Gas Producers," in vol. lxxxiv. of the *Proceedings Inst. C.E.* (1885), and the useful book of M. Jules Deschamps on "Les Gązogènes" (1902). Bischof invented his producer at a time when a good deal of attention was being given to the use of waste gases from coal-fired furnaces; and at that time the latter were more in favour among metallurgists because gas firing involved the use of a separate apparatus to produce the gas. Experiments with varying success were carried out, chiefly in Austria and France, but it was not till after F. Siemens (1857)

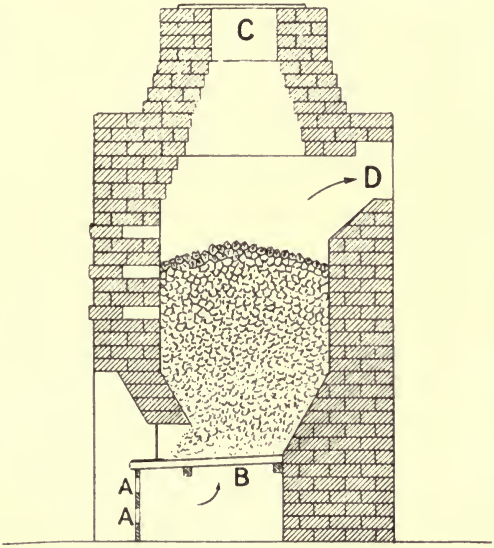

Fig. 9.—Bischof gas producer.

had invented his combined gas producer and regenerative furnace that the subject really made headway. The invention was introduced in this country by his brother, the late Sir William Siemens, and in 1861 he patented the arrangement shown in Fig. 10. This he described as follows:[1] "The regenerative gas furnace consists of two essential parts. The gas producer in which the coal or other fuel used is converted into a combustible gas, and the furnace, with its 'regenerators,' or chambers for storing the waste heat of the flame, and giving it up to the incoming air and gas." The air was drawn into the producer between the firebars **A**, while

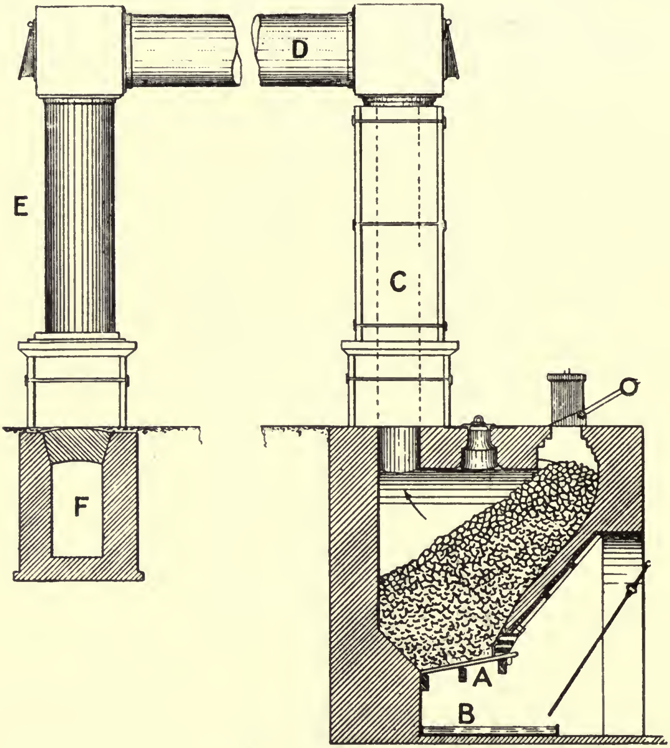

Fig. 10.—Siemens gas producer.

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[1] Crookes and Röhrig, vol. iii. p. 532. See also Percy's "Metallurgy (Fuel)," p. 524.

a certain amount of water in the trough **B** was vapourised by the heat of the fire above, and this water-vapour mixed with the air and was drawn with it into the fire. The theory of the action of this producer is similar to that of Fig. 2 (p. 7), and the following is given as the composition of the gas at the Glass Works of St. Gobain, France, the fuel used being a mixture of caking and non-caking coals :—

Carbonic oxide	23·7	per cent. by volume.
Hydrogen	8·0	,, ,,
Methane	2·2	,, ,,
Carbonic acid	4·1	,, ,,
Oxygen	0·4	,, ,,
Nitrogen	61·5	,, ,,
Total	99·9	

A novel and ingenious method was adopted for obtaining the necessary in-draught of air and for causing the gas produced to flow to the furnace. From the producer there was a vertical uptake **C**, usually built of brickwork, and from the top of this there was a long horizontal iron tube **D**, of large diameter, in the direction of the furnace; at the furnace end of the tube there was another vertical tube **E**, leading to the gas flue **F** of the furnace. The hot gas rose from the producer, and as it passed through the above-mentioned tubes its temperature fell considerably; consequently its density was greater at the furnace end, and this caused a suction and an in-draught of air at the producer end. In some cases the vertical cooling tube near the furnace was made longer than the uptake from the producer, so as to form a syphon with long and short legs. In connection with his gas producer Siemens used various furnaces of special construction, and a typical illustration is given in Fig. 11. It will be seen that under the bed of the furnace **A** there were four large chambers, **B**, **C**, **D**, **E**, packed loosely with firebricks. When the furnace was working, the hot products of combustion were made to pass downwards through two of these chambers, say **D** and **E**, while the air and gas passed upwards through **B** and **C** ; after a certain lapse of time, usually from 20 to 30 minutes, the direction of the currents was reversed by means of suitable valves, so that the products of combustion passed through **B** and **C**, and the gas and air through **D** and **E**. With regular reversals of the currents, it will be readily understood that the loose or chequered firebricks were highly heated by the outgoing products of combustion, while the gas and air were heated by passing over the highly heated surfaces of the bricks. Siemens called this a "regenerative" furnace, and although it would be more accurate to say that there was a recovery or accumulation rather than a regeneration of heat, the term is now an accepted one among engineers in this country. In France it is called *récupérateur*, and that is better. Be the name what it may, we are indebted to Siemens for showing us that with his particular combination of producer and furnace he was not only able to convert solid fuel of many kinds into useful gas, but that by this means very high temperatures could be developed. In fact, by his skilful combination of theory and practice he was able to effect economically many difficult operations, such, for instance, as the melting of steel and glass in open-hearth furnaces.

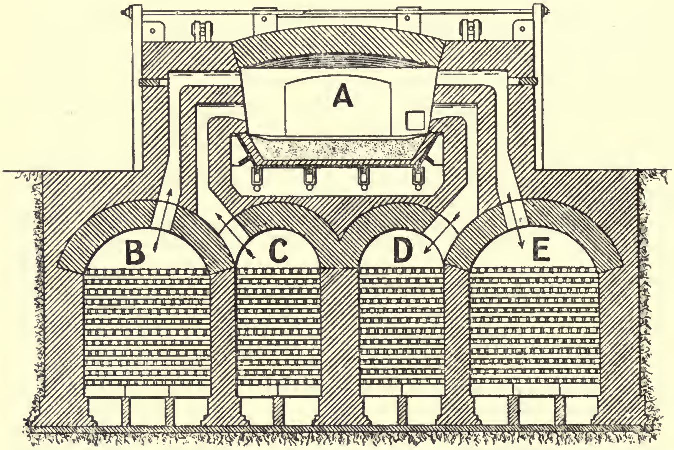

Fig. 11.—Siemens gas furnace.

In gas furnaces, however, as in other subjects, the process of development could not be stayed, and we shall presently record various improvements which have been introduced in more recent times. But before saying more about furnaces proper it will be convenient to trace some of the more noteworthy developments in gas producers. We have seen that Bischof and Siemens both made gas by drawing a current of air through an incandescent mass of fuel; but the production of gas by a chimney draught was slow and this led Siemens and others to try working their producers with a blast of air. The rate of combustion was quickened; but the heat was also intensified, and this favoured the formation of clinker, which adhered to the brick lining of the producer and caused serious trouble. Siemens tried closing the ash-pit of his producer and forcing in air by means of a jet of steam acting as an injector; but it was not successful, as the stepped grate he used involved a comparatively shallow fire and with this the decomposition of the steam and the reduction of the carbon dioxide were not properly effected. Various modifications of forced-draught producers with a steam jet were advocated from time to time, and this type of producer is now used more than any other. Among others Tessié du Motay (1871) introduced the producer shown in Fig. 12, the leading feature of which was a solid hearth **A**, without grate of any kind. Air at pressure and steam were admitted through the channels **B**, **B**, of which there were several in the plan view; the fuel was introduced through the hopper **C**, and the gas outlet was at **D**. This producer was extensively used in France and in the United States. In 1876 Brook and Wilson introduced the producer shown in Fig. 13; it also had a solid hearth **A**, and air was

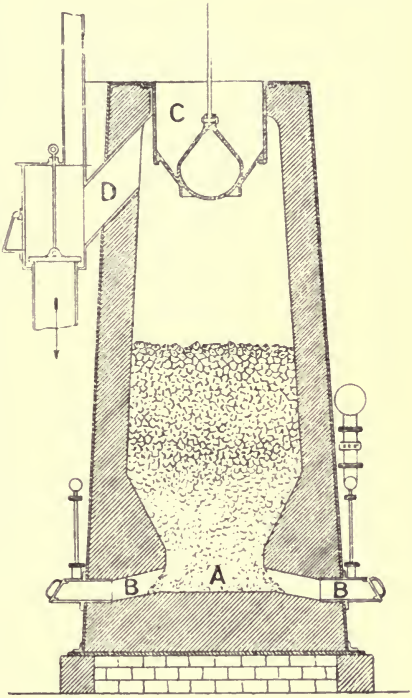

Fig. 12.—Tessié du Motay gas producer.

injected through the pipe **B** by a jet of steam at **C**; the fuel was introduced at **D**, and the gas passed into the circular flue or chamber **E**, and then through the down-pipe **F**. This formed the basis of the well-known Wilson producer, which has been used successfully for furnace work in several countries. The composition of the gas made in this producer with Durham coal was stated by Messrs. Pattinson and Stead to be as follows:—

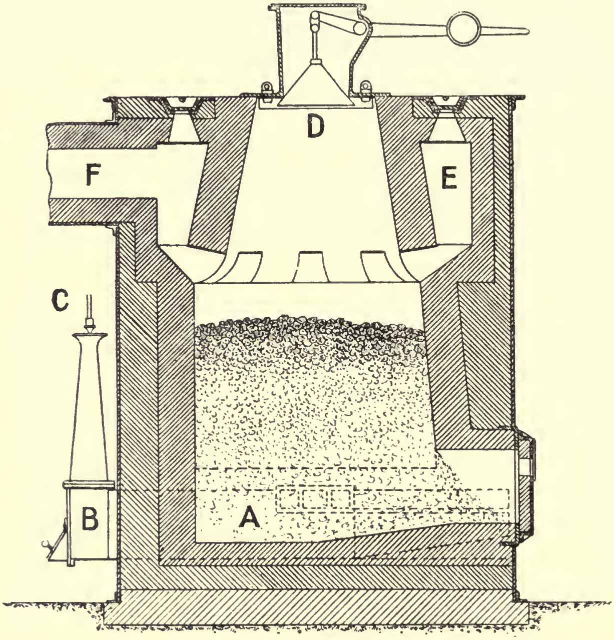

FIG. 13.—Brook and Wilson gas producer.

Carbonic oxide	26·8	per cent. by volume.
Hydrogen	11·5	„ „
Marsh gas	1·4	„ „
Carbonic acid	4·0	„ „
Nitrogen	56·1	„ „

In the gas producers now generally used for furnace work numerous modifications have been made in the details of construction. Many kinds of firegrates are used; some producers have rotating or moving grates, and others have water-bottoms, to facilitate the removal of the clinker; some are rectangular, but most of them are cylindrical; a few have an automatic feed for the coal; nearly all are worked with air injected by a jet of steam. As a typical modern example, we show in Fig. 14 a gas producer made by the Morgan Construction Co. (U.S.A.), and it will be seen that its various details have been carefully considered. Instead of a firegrate there is a tuyère with mushroom-shaped top, the air being injected by a jet of steam; the producer has a water-bottom for the removal of clinker and ash; but the special feature of the apparatus is the continuous automatic feeding device, consisting of an inclined, slowly rotating, water-cooled spout. By means of this the coal is not only fed at the rate required, but is evenly distributed over the surface of the fire. The makers of this producer have realised the importance of maintaining all the working conditions as uniform as possible, viz. the depth of fire, the removal of incombustible residues, and the prevention of clinker from adhering to the firebrick lining. These precautions favour uniformity in the quality of the gas, and a high heat efficiency.

In the practical working of gas producers which are supplied with air or with steam and air, the gas seldom contains less than 55, and sometimes as much as 65, per cent. of nitrogen. This inert gas is a distinct drawback (for reasons which will be given on p. 87), and about 1874 Lowe (U.S.A.) made a new departure altogether and produced what is technically known as "water-gas."[1] His apparatus is shown in Fig. 15. It consisted of a producer **A**, and two superheating chambers **B** and **C**, filled with loose firebricks. The fire was built up with anthracite or coke on the grate **D**, and was blown up with air at pressure entering at **E**. The gas thus produced left the outlet **F**, and at **G** it met a secondary supply of air (through the grating **H**), with which it was burnt; the flame and hot products of combustion passed downwards through the superheater **B** and upwards through **C**, and afterwards escaped as a waste product. In this way the brickwork in **B** and **C** became highly heated, and as soon as this was the case the two air-

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[1] *See* Chapter I., p. 17.

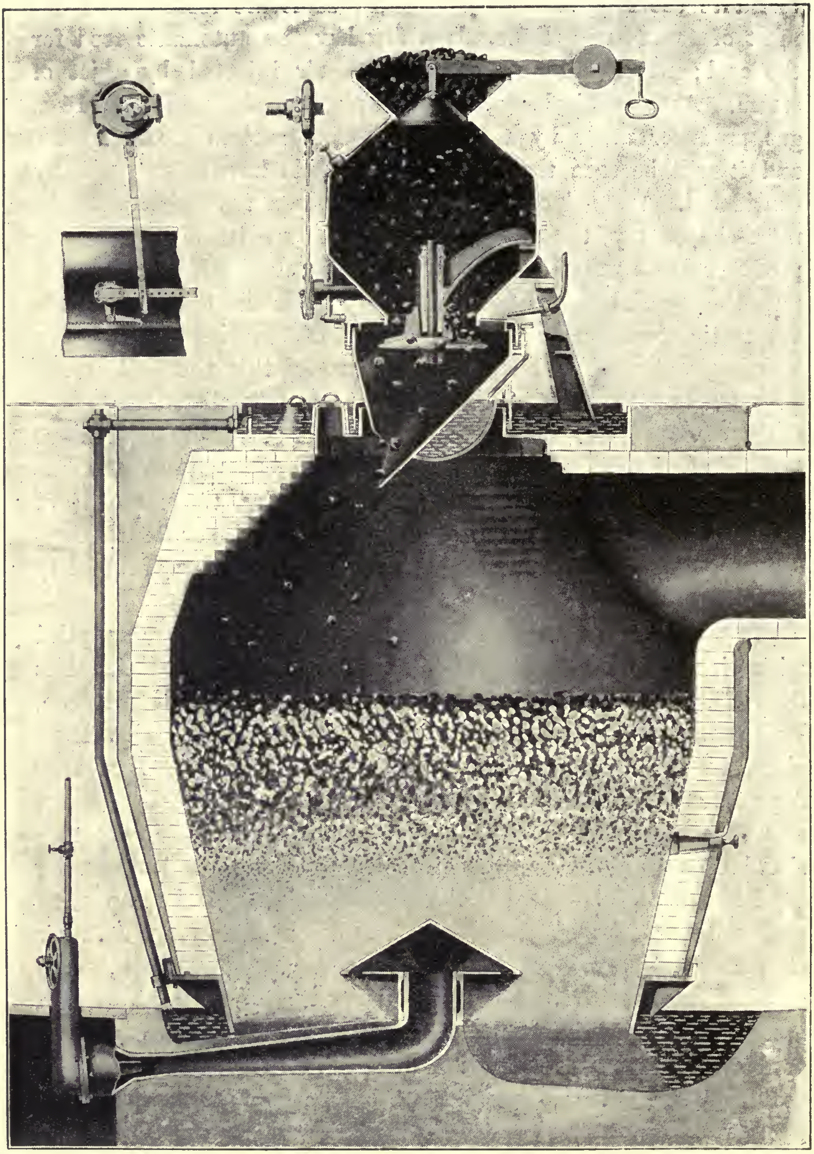

Fig. 14.—Morgan gas producer.

supplies were shut off, and steam at pressure was admitted at the top of **C**. It passed downward through **C** and upward through **B**, and then through **F** into the producer **A**, where it was decomposed on passing through the mass of incandescent fuel. The solid fuel resting on the grate **D** was put in through the doorway **I**; but, in addition to this, powdered fuel was sometimes fed in automatically from the hopper **J** during the period when steam was being admitted. This powdered fuel was met by the currents of highly heated steam, and part of the steam was then decomposed before it reached the incandescent mass. The other usual reactions occurred, and the gases formed left the producer

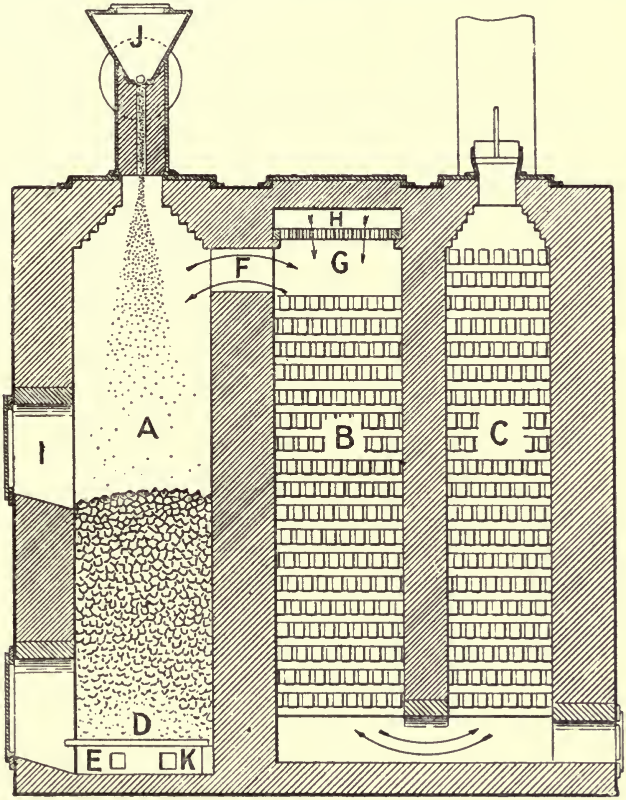

FIG. 15.—Lowe water-gas plant.

at **K**. One effect of sending steam only into the producer was to lower the temperature of the fire, and after a few minutes it was necessary to stop the steam-supply and turn on the air-blast again. The gases produced during the period of blowing up with air served to heat the chambers **B** and **C**, but they afterwards escaped at a high temperature, and this heat was lost altogether. Apart from this, the intermittent production of the water-gas is a drawback, and it is usual to pass the gas into one or more gasholders and to connect two or more producers to the latter, so that there may be a continuous flow of gas from the holder to the furnace, or wherever the gas is to be used. This adds considerably to the size and first cost of the plant, and its heat efficiency is necessarily low, as so much of the gas produced is wasted and the water-gas loses its sensible heat before it can be used.

The composition of the gas is usually given as follows:—

Carbon monoxide	44	per cent.	by volume.
Hydrogen	48	„	„
Carbon dioxide	4	„	„
Nitrogen	4	„	„

Allowance should, however, be made for the fact that the composition varies considerably between the times of starting and stopping each admission of steam. A further point to bear in mind is that at the end of the air-blast period the two superheating chambers **B** and **C** are filled with nitrogen and products of combustion, and when steam at pressure is introduced at the top of **C** the contents of **B** and **C** are driven backwards through the fire in **A**. This accounts in the main for the presence of nitrogen in the gas made during the steam-blast period.

Originally water-gas was intended chiefly for use in furnaces, but its intermittent production was a serious drawback, and it was seldom used for open-hearth operations. Its high calorific intensity was not an advantage for work of this kind, and the high temperature added greatly to the wear and tear of the furnace. Modern practice is therefore in favour of the ordinary producer, which can make gas continuously and without great fluctuations in its composition. Water-gas is, however, very useful for welding boiler tubes and similar work, and is more suitable for this purpose than ordinary producer gas because its flame temperature is much higher. But its chief use at the present time is as a basis for lighting-gas; it burns with a non-luminous blue flame, but when carburetted it gives an excellent light.

Messrs. Dellwik & Fleischer have devised a modified water-gas apparatus, in which the period of air-blow is greatly reduced. The essential features of the process are that the layer of fuel is not as deep as in other types of water-gas producers, and a rapid blast of air is used during the air-blow. The gases formed during the air-blow contain only 1 to 2 per cent. of carbon monoxide, the carbon being converted almost entirely to carbon dioxide. Less carbon is therefore consumed in raising the temperature of the fuel sufficiently for the production of water-gas. As there is no combustible gas formed during the air-blow it is necessary to burn additional fuel to raise steam in a separate boiler; but on the whole a considerable saving in fuel is effected compared with the type of water-gas plant in which air-gas is made alternately with water-gas. (See cols. 8 and 10, Table I.)

Having discussed the various types of producers used for furnace work, we will now revert to the furnaces themselves and consider briefly some of the improvements effected since the introduction of the Siemens system. One of the practical drawbacks in the Siemens regenerative furnace was that from defective construction or from cracks caused by expansion there was sometimes a leak of air into the gas chambers; or sometimes, owing to defective valves or their bad manipulation, a mixture of hot air and gas was formed. Explosions more or less serious ensued, and it became necessary to modify the system. Siemens admitted that his cooling of the gas was objected to on the score of wasting heat which might be used in the furnace. He argued, however, that this cooling of the gas was not wasteful, as its final temperature in the furnace did not depend on its initial temperature. He considered that if the gas were cooled before it reached the regenerative chamber of the furnace it would cool the outgoing products of combustion more thoroughly. He said,[1] "The only

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[1] Crookes and Röhrig, "Practical Treatise on Metallurgy," vol. iii. p. 537.

result, therefore, of working the furnace with gas of high temperature is to increase the heat of the waste gases passing off by the chimney flue."

Siemens heated both air and gas, but MM. Gaillard and Haillot, M. Pousard, and others simplified and improved the arrangement by conveying the gas direct from the producer to the furnace without cooling it, and by heating only the air by the outgoing products of combustion. The Gaillard and Haillot system of heating the air is shown in Figs. 16 and 17; in this the hot products of combustion from the furnace enter the air-heating arrangement at **A**, and flow through the horizontal passages **B**, **B**; they then pass away to the chimney flue **C.** The air for combustion of the gas in the furnace enters at **D**, and passes upwards through the perforated bricks shown in section in Fig. 17. In this way the air is highly heated by the waste products of combustion before it enters the combustion chamber through **E.** No unburnt gas can reach the air before the two meet in the combustion chamber, consequently there is no risk of explosion in any of the flues. Further than this, the flow of gas, air, and products of combustion is always in one direction, and the reversals

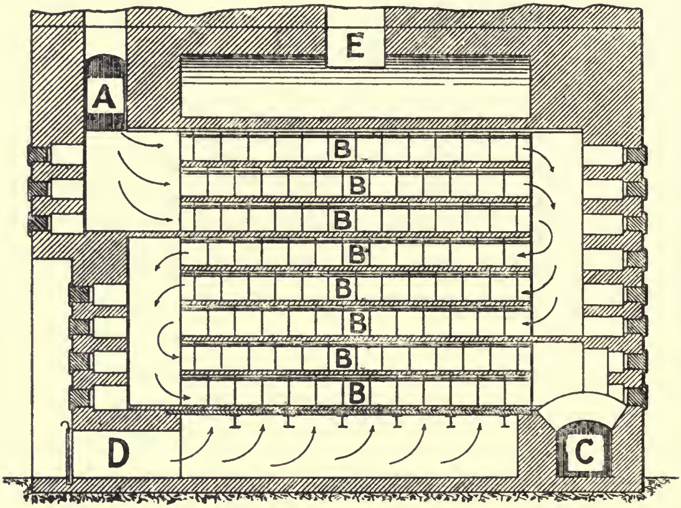

FIG. 16.—Gaillard and Haillot system of heating air—vertical section.

of the Siemens system are dispensed with altogether. Many modifications of the Gaillard and Haillot furnace have been introduced by engineers in this and other countries, but nearly all modern regenerative gas-heated furnaces follow the principle of heating only the air by the products of combustion, and of letting the currents of gas, air and products travel continuously in one direction. This not only simplifies the working of the furnace and materially reduces the risk of explosions, but lessens also the cost of construction and the ground space required.

In some operations it is better to have a higher temperature at one end of the furnace than at the other, so that the material put into the furnace may be gradually heated before it is subjected to the highest temperature required. For this purpose it is better to let the flame travel always in the same direction, and then by regulating the admission of air it is possible to make the flame longer or shorter as required. In this way the character of the flame may also be varied to a considerable extent so as to have an oxidising or reducing action as may be desired, as already explained (p. 66).

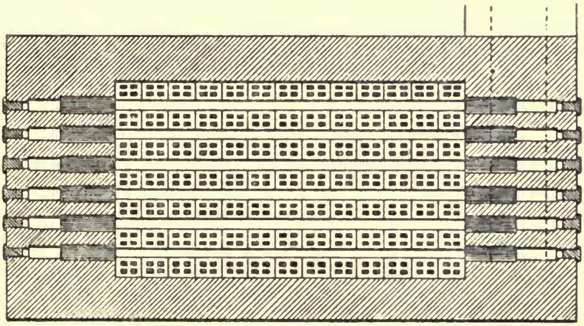

Fig. 17.—Gaillard and Haillot system of heating air—sectional plan.

In some furnaces, as in those for heating billets of iron or steel, annealing iron plates, etc., it is desirable that the temperature should be uniform throughout, and within certain limits this can be effected with the flame travelling always in one direction. In Figs. 18 and 19 we have shown a typical reverberatory furnace of this kind; the hot gas from the producer passes through the brick flue **B** and valve **C** to **D**, and it meets hot air at **E**; the mixture of gas and air passes through the chequered brickwork **F** and burns in the furnace **G**; the products of combustion pass through **H** into the flues **P, P**, which lead to a flue **I**, and thence to a chimney in any convenient position; the air for combustion is heated by passing through the flues **A, A**. A furnace of this design, with a floor 8 ft. long by 4 ft. wide, has been used for heating billets of steel before compressing them into the form of shells for projectiles.[1] In the same works there were other furnaces of the same size, used for the same purpose, but heated by ordinary fires. A competitive trial lasting twelve hours was made with the gas-fired furnace and one of the other furnaces. Each furnace had a separate gang of men and a separate hydraulic press; the competition was keen and the result was that the gas producer for the gas-fired furnace consumed 765 lbs. of coal, while the furnace with a fire consumed 1276 lbs., a saving of 40 per cent. in favour of gas. If the furnace is long and if it is necessary to have equal heating throughout, it is best to reverse the direction of the flame periodically as in the early Siemens

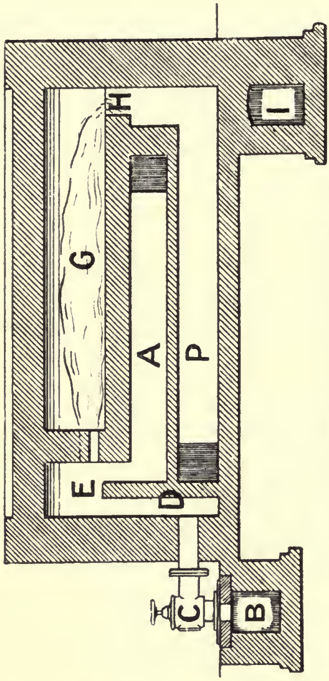

Fig. 19.—Gas-heated reverberatory furnace—longitudinal section.

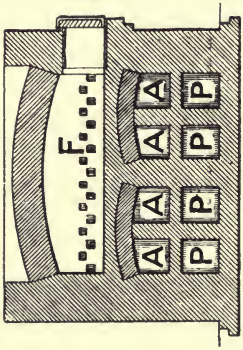

Fig. 18.—Gas-heated reverberatory furnace—transverse section.

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[1] *Proc. Inst. C.E.*, 1897, vol. cxxix. p. 221.

furnace. To give a practical instance, we had to design a gas-heated furnace 20 ft. long by 12 ft. wide inside, for the purpose of heating armour plates to an even temperature throughout at the works of Messrs. Brown & Co., of Sheffield. Each plate was over 300 mm. (say 12 ins.) thick and weighed over 20 tons, and as it had already been shaped by costly processes it was important that there should be no distortion during the heating. Attempts had previously been made with fires and had failed because some parts were over-heated while others were under-heated. In the gas furnace we reversed the flames as in the Siemens furnace at intervals of about 30 minutes, and we heated the air by the waste products of combustion; but we took the hot gas direct from the producers to the furnace and did not heat it further by passing it through regenerative chambers. The result was satisfactory in every way and it showed incontestably the superiority of heating by gas for work of this kind. Moreover, the average consumption of fuel in a month's work was only 185 kilos (407 lbs.) per ton of plates heated, including the heat losses during the discharging and recharging of the furnace after each heating and all other sources of loss.

In many operations, such as the annealing of glass or wire, the enamelling or glazing of various materials, it is necessary to heat them gradually, then to heat them to a high temperature and maintain them at that heat, and afterwards to cool them gradually. It is usual to do this in an oven or chamber, and the brickwork of the oven, as well as the materials it contains, must be heated and cooled for each charge of materials treated. This necessarily involves a considerable loss of heat; and the wear and tear of the oven is also excessively great, owing to the frequent expansion and contraction of the brickwork and to its injury by hard firing to get up the maximum heat required. In some glass-works this is avoided, in connection with the annealing of large sheets, by using a long oven or furnace which is maintained at a moderate heat at the charging end and at the maximum heat required in the middle. The discharging end is not heated. The glass to be annealed is mounted on a waggon, and this waggon is pushed or drawn through the oven from end to end at the speed required. In this way there is a gradual heating of the glass after it enters the oven; it is then highly heated, and afterwards it is allowed to cool gradually. Mr. Dowson followed this principle in designing a continuous furnace for the British Aluminium Co. for the purpose of carbonising large blocks of material for use at their electrolytic works. Fig. 20 represents the cross-section of this, and Fig. 21 a sectional plan. The blocks to be carbonised were packed in iron boxes **A**, **A**, and these were carried on a waggon with open framing which supported a floor of firebricks, so that the ironwork of the waggon was protected from excessive heat. On each side of the waggon there was an iron projection which dipped into the grooves **B**, **B** filled with sand, and thus cut off the connection between the upper and lower parts of the furnace; this protected the lower part of the waggon and ensured the passing of hot products of combustion through the upper part of the furnace only. The whole length of the furnace was kept full of waggons; they entered through a door at **C** from a turntable **D**, and were pushed into and through the furnace by a hydraulic ram.

Gas was burnt in the middle length of the furnace **E**, and the hot products of combustion passed through the length **F** to the chimney **G**; the length **H** was used for cooling, and was not heated. Gas from the producer was admitted on each side of the furnace through the valves **I**, **I**; air entered at **C** and travelled along under the waggons until it reached the part **E**, when it passed up the flues to burn with the gas; the air was heated by coming in contact with the hot bricks forming the floors of the waggons. The heating was continuous night and day, and the temperature in the length of furnace **E** was about 1000° C. (about 1800° Fahr.). To maintain this heat uniformly and to carry on the process of carbonising, the consumption of local coal was only about 76 kilos per hour. Apart from the economy effected, the advantage of this system was that the material to be treated was gradually raised in temperature in **F** until it reached the maximum temperature in **E**; after this, its temperature was gradually lowered by passing through **H**. A gas-fired furnace of this kind can doubtless be used with advantage for many manufacturing processes in which it is necessary to heat materials gradually, then to heat them highly, and afterwards to cool them gradually.

One case we dealt with was at a pottery in Staffordshire

There was a horizontal kiln, which was formerly heated by a large coal fire, for glazing porcelain cups, saucers and plates; and

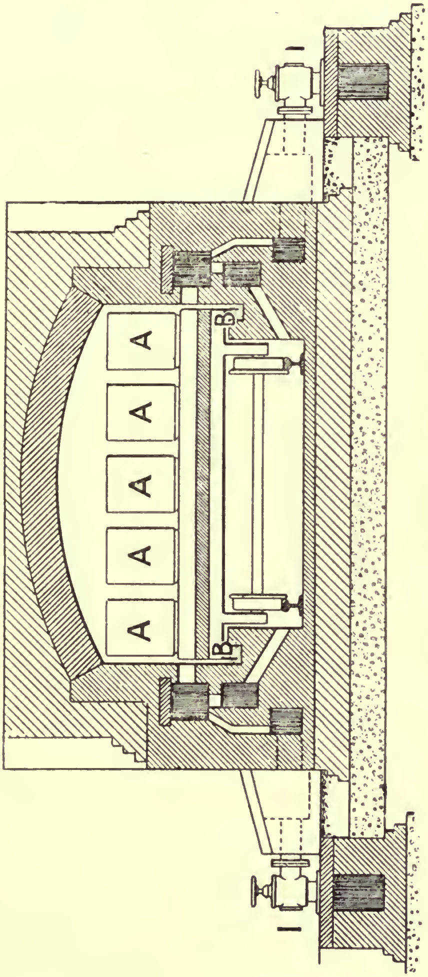

Fig. 20.—Continuous furnace—cross section.

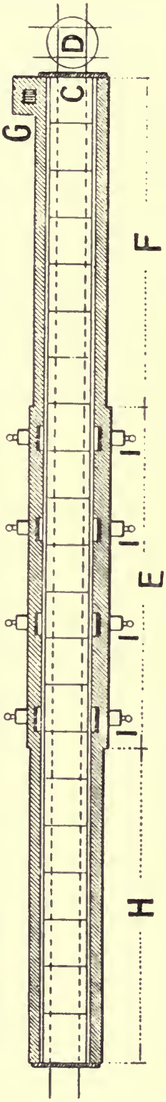

Fig. 21.—Continuous furnace—sectional plan (reduced scale).

instead of the fire we introduced producer gas. With the latter there was some saving in fuel, but the chief gain was that the heat was more uniform, and there was no loss from under-firing or over-firing of the goods. This was considered of great importance as a large proportion of them was spoiled when the kiln was fired in the usual way.

The heating of steam-boilers may not belong strictly to furnace work, but as we are often consulted on the subject and as we know that many are interested in it we think it may be well to add a few words about it. Several attempts have been made to heat boilers with producer gas; but the results are not encouraging, and our opinion is that from the point of view of fuel economy there is little hope of success. In a boiler fired in the ordinary way the mass of incandescent fuel is within the boiler, and a large amount of heat is radiated from it; but when the fuel is converted into gas in a separate producer the incandescent fuel is away from the boiler proper. There is also a loss of heat in the process of conversion. These drawbacks are partly compensated for by less air being required, but when the gas comes in contact with the comparatively cool metal surfaces of the boiler its temperature is lowered and the combustion is incomplete. In the practical working of the two systems the removal of the clinker is more difficult in a gas producer than in a boiler, and more labour is required. As an example, we may mention what we have seen at a mill near Milan. There were twenty-one large steam-boilers of the Cornish type, and four of them were heated with producer gas. With cheap Scotch coal the gas-fired boilers usually evaporated 7 kilos, but occasionally 7½ kilos, of water per kilo of coal; the other boilers had mechanical stokers and were fired with Cardiff steam coal, and they evaporated 10 kilos of water per kilo of coal, but this coal cost 5 francs per ton more than the Scotch coal. Apart from the question of labour, the general result was rather in favour of the ordinary firing; and moreover the cost of labour was a good deal higher for the gas firing. At a large steel-works in Cleveland, U.S.A., where there were many gas producers in use, numerous experiments were made, and the general conclusion was that there was no saving in firing steam-boilers with gas. If there is any chance of success it would appear to be in the direction of combining the boiler and producer; some attempts have been made, but so far as we are aware they have not been entirely successful.

CHAPTER V

HEATING WORK (VARIOUS)

In the previous chapter we have dealt with producer gas for furnaces and similar work in which large flames are required; we will now consider its use for other kinds of work which require the use of burners and small flames. When burners and cocks are used it is essential that the gas should be clean, and it is obvious that it cannot be taken direct from the producer to the burners, or the latter would soon be clogged with troublesome deposits. In practice this usually means that the gas is passed through water, and scrubbing material such as coke; incidentally the gas is cooled to about the temperature of the surrounding air, and this not only means that the bulk of the sensible heat which the gas carries with it from the producer is lost, but that any condensable hydrocarbons which leave the producer in the form of tarry vapours are lost also.

When burners are used it is also important that the gas pressure at the burners should be constant, so that the heat given off by the flames may be kept uniform or varied at will by cocks on the supply pipes. For this reason the gas must be passed through a gasholder, or its pressure must be regulated in some equally efficient manner. As producer gas always contains a large proportion of nitrogen, and as its flame temperature is comparatively low, it is important not to use more air than is strictly necessary to ensure complete combustion. For this reason it is also undesirable to use "atmospheric" burners when small jets of producer gas are required; in such cases it is better to use plain burners with holes in them, usually not much under 2 to 3 mm. (say $\frac{1}{8}$ in.) diameter. When larger jets of gas are used atmospheric burners may be employed, or air at pressure may be mixed with the gas on its way to the burner; but in the latter case the adjustment of air to gas should be regulated carefully, to prevent the formation of an explosive mixture in the pipes. The advantage of forcing air into the gas is that an intimate mixture of gas and air is then formed, ready to burn quickly as soon as it is ignited. The flame is, therefore, shorter than it would be if it merely came in contact with the air surrounding its outer surface; and as a consequence of this a greater intensity of heat is produced, and the heat is concentrated on the object to be heated. For example, it is essential that blowpipes should have air at pressure, and with producer gas of good quality it is best to use an air-pressure of 0·10 to 0·15 kilo per sq. cm. (1½ to 2 lbs. per square inch). This is a higher pressure than is generally used for ordinary town gas, and the probable explanation is that as the quantity of the weaker gas which must be burnt is much larger a higher air-pressure is necessary to ensure a sufficient quantity being mixed with the gas before the latter is ignited.

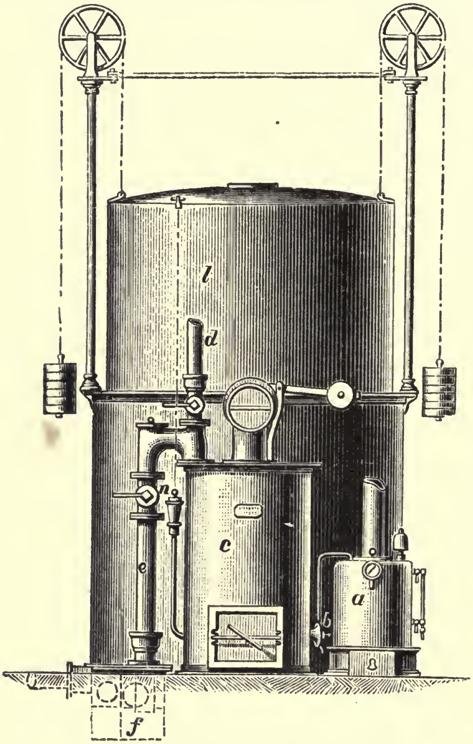

Fig. 22.—Early Dowson gas plant.

In all these cases it is manifestly important that the gas-pressure should be constant, so that the air-supply may be regulated to give the best effect. Owing to the comparatively low flame temperature of producer gas and to the liability of this temperature being still further reduced if the gas is wrongly used it is specially important that the best way of burning the gas in small quantities should be carefully considered in all cases.

For such work as we have referred to, the presence of a large proportion of nitrogen is a serious drawback ; in fact, all producer gas made with air only may be ruled out at once. It cannot be used with small burners, nor can other producer gas with a low percentage of hydrogen, because gas of this nature, when it is cool, has such an exceedingly low flame temperature. To get a high enough flame temperature and to get gas of sufficiently high calorific power to be used with air at pressure it is necessary to keep the percentage of incombustible gases as low as possible. It has been shown in Chapter I. that, apart from water-gas, the richest gas is obtained when the maximum quantity of steam is decomposed with the formation of carbon monoxide and hydrogen. When Mr. Dowson first took up the subject he endeavoured to carry this out in a practical way, and the apparatus he devised between 1878 and 1881 is shown in Figs. 22 and 23. In these figures *a* represents the apparatus in which steam was produced and superheated ; *b* is an air injector worked by a jet of steam at pressure from *a* ; *c* is the gas producer, with a chimney or waste-pipe *d*, and a down pipe *e* ; *f* is a hydraulic box containing a water seal ; *g* is the inlet pipe and *m* the outlet pipe of the gasholder *l*. Inside the tank of the gasholder there is a cylindrical coke scrubber with a vertical partition down the middle ; the half *h* acted as a wet scrubber and had water-spray pipes *i*, *i*, and a water-feed *j* ; the other half of the scrubber, *k*, was dry. To govern automatically the production of gas to suit a varying rate of consumption a pipe leading from the lower part of the gas producer had a loose conical plug *n*, fitted into a suitable seating, and this plug was attached to a chain which was fixed to the top

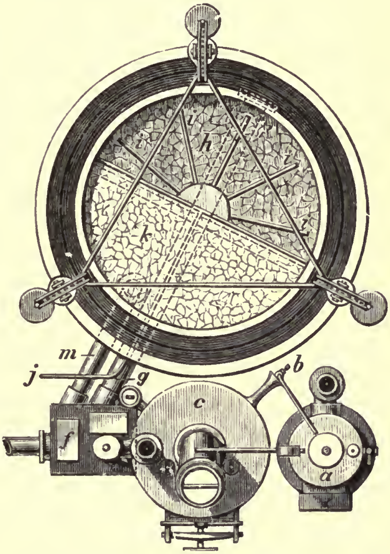

Fig. 23.—Early Dowson gas plant—sectional plan.

of the gasholder. It was so adjusted that when the gasholder was nearly full of gas the plug *n* was lifted, and allowed some of the steam and air to blow off, instead of all being passed through the fire. When the gasholder fell the plug *n* was closed, and gas was made at the maximum rate until the gasholder was full again.

The late Prof. William Foster gave the following analysis of gas made in this apparatus:[1]—

Hydrogen	18·73	per cent.	by volume.
Marsh gas	0·31	,,	,,
Olefiant gas	0·31	,,	,,
Carbon monoxide	25·07	,,	,,
Carbon dioxide	6·57	,,	,,
Oxygen	0·03	,,	,,
Nitrogen	48·98	,,	,,
Total	100·00		

The process of making the gas resembles in principle that adopted in some of the producers referred to in the preceding chapter; but there was not only a producer but a complete set of apparatus for cooling and cleaning the gas, and there was also a small gasholder. The gas was made with small anthracite, and special means were adopted for producing and *superheating* the steam required; the thermal and other working conditions favourable to the necessary reactions in the producer were also carefully attended to. As a result there was a much higher percentage of hydrogen, and notwithstanding the cooling and cleaning of the gas and the consequent removal of the condensable hydrocarbons its calorific power (1432 calories per cubic meter or 161 Brit. T.U. per cubic foot) was higher than in any producer gas made before that date.

This apparatus was shown working at the Smoke Abatement Exhibition (1881–1882), and was tested by Mr. D. K. Clark on behalf of the Committee,[2] who awarded the exhibitor a gold medal, and a special prize of fifty guineas given by the late Sir William Siemens for "The best method or arrangement for utilising fuel as a heating agent for domestic and industrial purposes, combining

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[1] *Proceedings Inst. C.E.*, 1882, vol. lxxiii. p. 320.

[2] Official Report of Smoke Abatement Committee, 1882.

the utmost economy with freedom from smoke and noxious vapours." The report states that "the steam producer and superheater consists of a long coil of tube of such a form that nearly all of it is exposed to the action of the gas-flame. Water is forced under a pressure of 20 to 25 lbs. per square inch into the coil, in which it is converted into superheated steam. The gas required for heating the coil is drawn from the gasholder." During a test lasting three hours five minutes water was consumed at the rate of 7·8 lbs. per hour, and the consumption of gas for converting the water into superheated steam was at the rate of about 100 cub. ft. per hour. The gas was generated at the rate of 1175 cub. ft. per hour, after deducting the above allowance for making steam. Gas was made with anthracite, and the fuel consumption was reported to be at the rate of 12·13 lbs. per 1000 cub. ft. gross passed into the gasholder, and at the rate of 13·17 lbs. per 1000 cub. ft. net, after deducting the gas used for making the steam required.

One of the early installations carried out by Mr. Dowson was at the Gloucester (second) County Asylum in 1885, and from that date to the present time it has been used there regularly for all the cooking, baking bread, etc., for the staff and inmates, also for driving a gas-engine for pumping water, etc. At this place there is a large meter which registers all the gas consumed, except that used for the gas-engine which is served by a separate main. The clerk of the works reported on the cost of production for the year ending March 31, 1895, as follows:—

	Cubic feet.
Gas produced (measured by meter)	22,211,700
Estimated quantity used for engine pumping three hours a day, at 3000 cub. ft. per hour (not registered) . . .	3,285,000
Total quantity produced . .	25,496,700

Details of material and labour used in the production of the above quantity of gas:—

	£	s.	d.
Anthracite coal, 124 tons 19 cwts. at 21*s*. 2*d*. a ton . .	132	4	10
One year's repairs to plant at 6*d*. a day	9	2	6
Gasman's wages, making gas only, at 21*s*. per week . .	54	12	0
	195	19	4

thus costing 1⅞*d*. per 1000 cub. ft., exclusive of slack used for the steam-boiler.

[Steam for the gas plant was generated in a small vertical boiler, and this boiler was fired with cinders, etc., from the various fires in the asylum ; no account of these was kept, as they were treated as waste for any other purpose. If fuel for the boiler were included, the cost of the gas would be about 2*d.* per 1000 cub. ft.]

The cooking and heating apparatus were tested by the architects, Messrs. Giles & Gough, and the following results are taken from their report to the Building Committee of the Asylum (1883):—

Large roasting oven.

Initial temperature of oven, 57° Fahr.

Dowson's gas consumed, 60 cub. ft. to raise oven to 300° Fahr.

Time occupied, 9 minutes to raise oven to 300° Fahr.

Gas consumed at the rate of 250 cub. ft. per hour to maintain temperature of 300° Fahr.

(NOTE.—This oven had been previously tested with town gas at the Smoke Abatement Exhibition, and then took 15 minutes with a consumption of 30 cub. ft. to raise the temperature from 58° to 300° Fahr., and it afterwards required 90 cub. ft. per hour to maintain the temperature of 300° Fahr.)

Three coppers in scullery.

Filled in each 20 gallons of water at 57° Fahr.

Lighted gas		5.20 p.m.
Temperature,	150°	6.5 „
„	168°	6.20 „
„	190°	6.30 „
„	205°	6.40 „
„	212°	6.47 „

Dowson's gas consumed, 1400 cub. ft.

Result.—60 gallons boiled in 1½ hours, with consumption of 1400 cub. ft. of gas, requiring 19 lbs. of coal, and costing under 4½*d.*, including wages.

Laundry copper.

Filled in 60 gallons of water at 62° Fahr.

Result.—60 gallons boiled in 2½ hours, with consumption of 1575 cub. ft. gas, requiring 19½ lbs. of coal, and costing 4½*d.*, including wages.

They added, "With the gas system the coal consumption is about half that usually required for heating by coal fires."

To compare with this, it may be interesting to note that a thin steel copper of similar shape set in firebrick with a coal fire, as supplied to the War Office, was tested officially and gave the following results : 21 gallons of water at 58° Fahr. boiled in three-quarters of an hour, with a consumption of 15 lbs. of coal. This was the best type of copper fired with coal or coke.

Although the gas tests above referred to are not of recent date, they are given, not only because they were made carefully under working conditions, but because the gas made in more recent plants has about the same calorific power, and because there was a large meter to register all the gas consumed. It is seldom that this useful instrument forms part of the equipment of a heating gas installation.

In 1900 the gas plant at the Gloucester Asylum was extended, and in 1905 the Clerk of Works reported that the consumption of gas was then at the rate of about 36½ million cub. ft. per annum. The following details were also given :—

Bakehouse.—The ovens were heated 74 hours a week, with a consumption of 131,600 cub. ft. of gas. The flour used = 27 sacks of 280 lbs. each.

Kitchen.—The average consumption of gas is as follows :—

6 a.m. to 9 a.m.,	at 4000 cub. ft. per hour	= 12,000 cub. ft.
9 „ to 1 p.m.,	at 8000 „ „	= 32,000 „
1 p.m. to 5 „	at 4000 „ „	= 16,000 „
5 „ to 10 „	at 1000 „ „	= 5,000 „
	Total per day . .	65,000 „
	Total per week . .	455,000 „

A more recent installation of a somewhat similar kind is at the Isolation Hospital of the Urban District Council of Walthamstow. It was started in 1900, and the gas is used for all the cooking and heating of water (including baths) in the administrative block. There are also four independent blocks or pavilions for patients, and at each end of each of these blocks there is a gas-fired boiler of the geyser type, to provide hot water for the baths, lavatories, etc. Fig. 24 is reproduced from a photograph of the kitchen.

Another interesting installation is at the well-known cocoa factory of Messrs. Van Houten & Son at Weesp, in Holland. This plant was started in 1885, and has been working regularly since that date. A representation of the plant is shown in Fig. 25. There are eight gas producers, each capable of producing 453 c.m. (16,000 cub. ft.), or a total of 3625 c.m. (128,000 cub. ft.) per hour. The gas plant is outside the town, about a quarter of a mile from the factory, and the gas travels through a main 2 ft. in diameter which passes under a canal. The gas is used chiefly for roasting cocoa beans, but it is also used for soldering tin boxes,

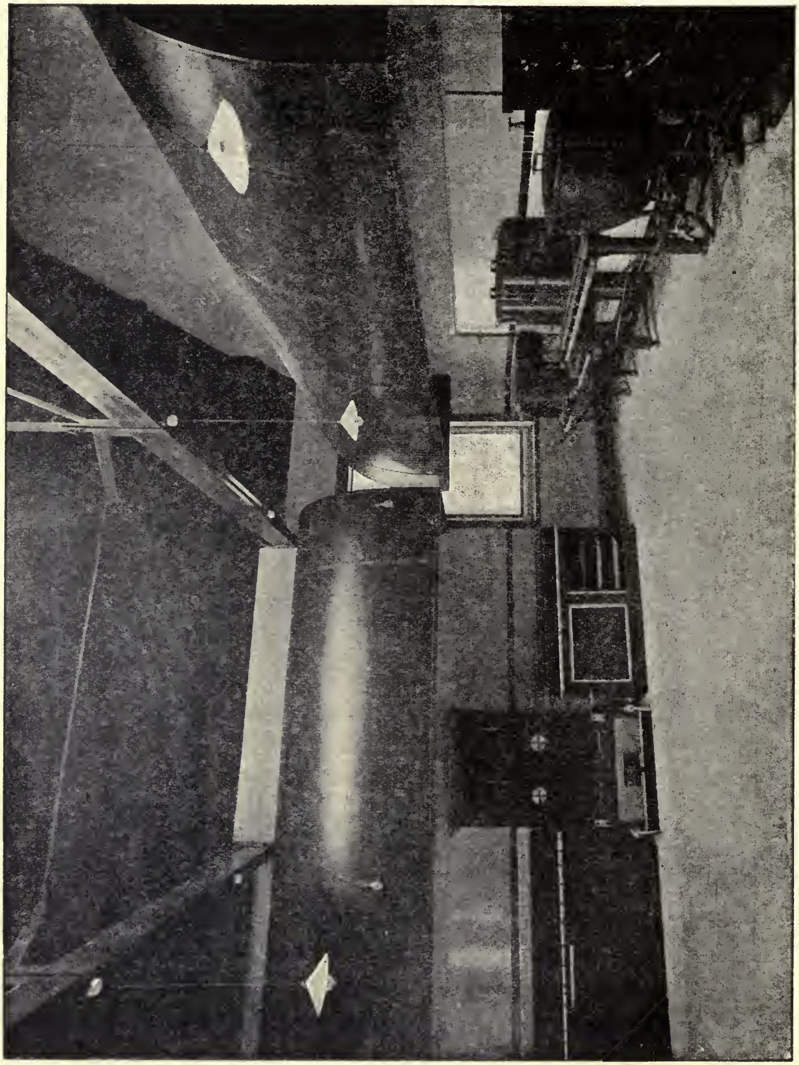

Fig. 24.—Kitchen at Isolation Hospital, Walthamstow.

and for other heating work, as well as for heating stoves in several work rooms and offices. When the plant was started, the cost of

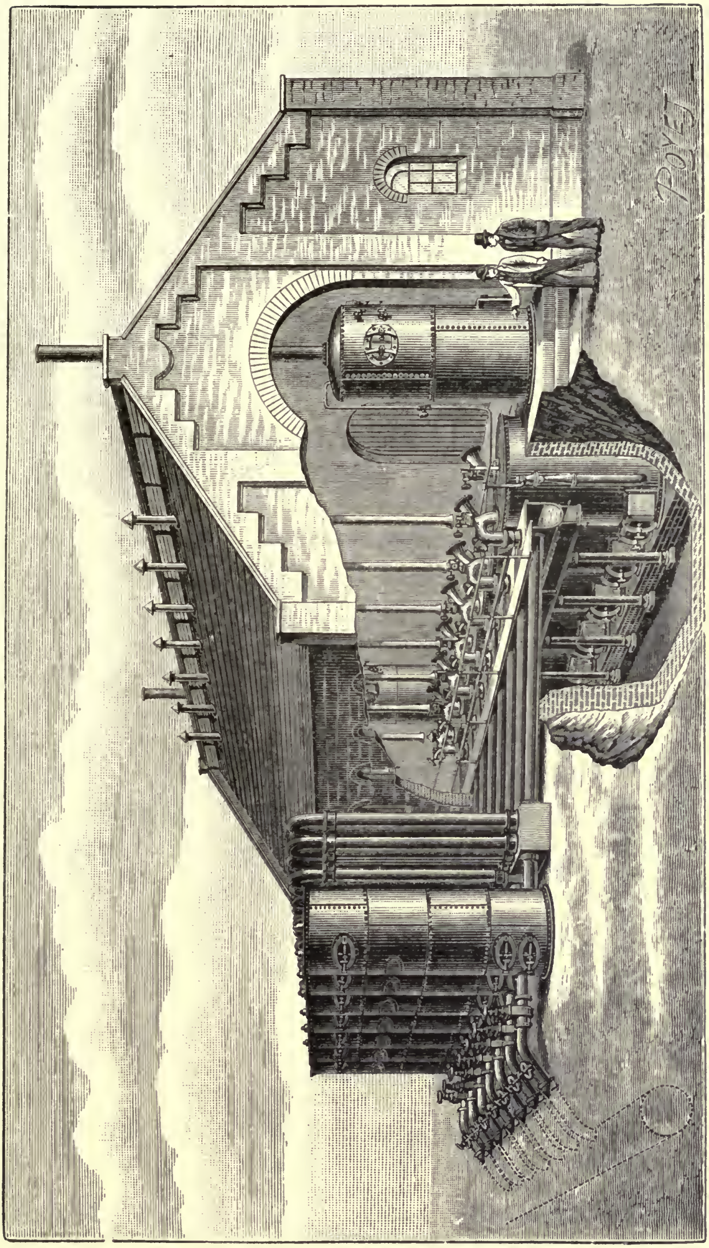

FIG. 25.—Dowson gas plant at Weesp, Holland.

anthracite was 16*s.* a ton, and careful tests showed that the calorific power of the gas was one-fourth that of town gas, and that its cost was 1¾*d.* per 1000 cub. ft. (including fuel and wages). This would give 7*d.* for the equivalent of 1000 cub. ft. of town gas; but at the present average price of anthracite the cost would be 8*d.* instead of 7*d.*

This gas is used in several other factories for roasting cocoa, coffee, and other food products. The following are the results of trials with two different samples of coffee:—

	Trial No. 1.	Trial No. 2.
Speed of roaster (revolutions per minute)	58	58
Air pressure (pounds per square inch)	4½	4½
Gas alight (minutes)	33½	34½
Coffee in roaster	35½	37
Producer gas consumed (cubic feet)	335	320
Weight of coffee roasted (pounds)	56	56

One great advantage of roasting by gas, compared with a coke fire, is that the heat can be better regulated; another is that the gas can be turned off at the critical moment, just when the roasting is done. It is well known that the roasting of coffee, for instance, is an operation of great nicety; if it is insufficiently roasted much of its aroma is lost. It is said that with gas-roasting the weight of finished coffee is 10 to 15 per cent. greater than with a coke fire.

The various kinds of heating work for which producer gas is used are too numerous to mention, but the following are some of those with which we have had to deal:—

Japanning and enamelling stoves.
Cutting and finishing glass.
Type-founding machines.
Crucible furnaces.
Varnish-making.
Tailors' irons in clothing factories.
Laundry irons, calenders, etc.
Machines in boot factories.
Drying wood, for musical boxes, etc.
Gassing silk and cotton yarns.
Singeing textile fabrics.
Soldering biscuit and condensed milk tins, etc. (At the factory of the Société Nestlé each girl solders from 4000 to 5000 tins each day of ten hours.)

Brazing with blowpipes.[1]

Small furnaces for hardening, tempering, annealing, etc. (At the Birmingham Small Arms Factory there are about forty of these furnaces in use.)[1]

Expanding wheel rims and tyres.[1]

Annealing cartridge cases, as at the Royal Arsenal, Woolwich.[1]

Speaking generally, we have found that four volumes of the gas made in the Dowson apparatus are equivalent to one of ordinary town gas; but for blowpipes and some other special work it is best to allow rather more.

In connection with cooking and baking or the roasting of food materials by heat derived from the combustion of producer gas it is well to consider whether any deleterious effect is caused by the contact of products of combustion with the food. Our opinion is that no harmful effect is produced, especially as there must be a fairly free and rapid escape of the products of combustion to ensure a sufficient in-draught of air to burn the gas in the oven or stove in which the food is cooked. It has been well established by competent authorities that no deleterious effect is produced when ordinary town gas is used for cooking. The products of combustion of this gas consist chiefly of carbon dioxide and water-vapour, with a very small percentage of sulphurous or sulphuric acid. The accompanying nitrogen is a neutral body, and the mere traces of other gases are negligible. When producer gas is used, the products of combustion are similar in kind to those of town gas, although the proportions of carbon dioxide and water-vapour differ. As to the sulphur compounds, the sulphur does not exceed in amount that derived from ordinary town gas, provided the coal from which the producer gas is made does not contain more than about 0·5 per cent. of sulphur. It will be remembered that producer gas, as now ordinarily made for heating work, is merely washed and scrubbed. Except in special cases it is not purified chemically, as in the case of town gas; but purification, when necessary, presents no great difficulty. The water through which the producer gas is passed takes up some of the sulphuretted hydrogen, but the total quantity of the latter which is in the gas is usually so small that it is neglected. If in

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[1] For work of this kind an air-pressure of 1½ to 2 lbs. per square inch is recommended, but with this air-pressure the gas must be of good quality.

special cases it is considered desirable to remove the sulphuretted hydrogen this can be easily effected by passing the gas through a purifier containing iron oxide, as in town gasworks.

In some industrial processes, such, for instance, as japanning and enamelling, some of the constituents of the japan or enamel, which consist largely of coal-tar products, are injuriously affected by the sulphur compounds in the products of combustion of producer gas. These affect also the colours of certain metallic paints, *e.g.* the so-called "gold paint," which is made with copper and is readily tarnished by sulphuretted hydrogen. Without purifying the gas these troubles can be avoided by heating the stoves or ovens in such a way that the gases (burnt or unburnt) do not come in contact with the materials to be heated; or the gas can be purified as described above.

CHAPTER VI

ENGINE WORK

Gas-engines were invented long ago, but the early ones were not successful; in fact, they were not "within the range of practical politics" until Dr. Otto introduced his four-stroke cycle. His engine was patented in 1876, and it is since then that a real gas-engine trade has sprung up. The makers in Germany and in England were energetic and skilful; and they not only achieved a remarkable success but prepared the way for numerous other makers, who adopted the Otto principle as soon as the master patent expired.

At first all gas-engines were worked with town lighting gas, and the conditions of working were almost ideal compared with steam power. The user of the engine needed no storage of fuel, no tall chimney; and no ground space was required for a steam-boiler. There were no boiler repairs, no ashes to remove, no banking of fires and stand-by losses, no smoke nuisance; and the engine could be started or stopped at a moment's notice. The attendance, and consequently the expenditure in wages, were nominal; the only drawback was the price of the gas. An engine worked with costly gas is, in fact, analogous to an electric motor worked with current derived from zinc as the fuel. Still even with expensive town gas small gas-engines competed successfully with steam-engines and boilers; but for 20 B.H.P. and upwards the working cost of a gas-engine with such a costly fuel as ordinary lighting gas was greater than that of steam power. A new field of enterprise was opened out when it was proved that a gas-engine could be worked successfully with semi-water-gas, because the low cost of the latter enabled the gas-engine of any size to beat the steam-engine in cost of working.

The first trial of a gas-engine with producer gas was in 1879, with a set of Dowson's gas plant[1] (see Figs. 22 and 23, pp. 86, 87). His attention was drawn to the subject in 1878, while he was engaged in perfecting an apparatus for making cheap gas for heating purposes, and it occurred to him that it might be eminently suitable for gas-engines. The English makers of the Otto engine were sceptical as to the result, as they considered that no gas with a high percentage of nitrogen could succeed. They were, however, persuaded to make a trial at their works with a little engine developing about 3 B.H.P., and their adverse opinion was so far broken down that further trials were made in the following year. Mr. Dowson read his first paper on the subject at the York meeting of the British Association for the Advancement of Science (1881),[2] and he then showed a small Otto engine working with his gas plant. This same engine and plant were afterwards tested by Mr. D. K. Clark, at the Smoke Abatement Exhibition, on behalf of the Committee. He reported as follows[3] :—

Engine developed 4·41 I.H.P. and 3·26 B.H.P. when making 156 revolutions per minute.
Gas consumed per I.H.P.-hour, 110·34 cub. ft.
Gas consumed per B.H.P.-hour, 149·30 cub. ft.
Fuel consumed per I.H.P.-hour, 1·45 lb.
Fuel consumed per B.H.P.-hour, 1·97 lb.

For various reasons much better results can be obtained with engines of recent date, but at the time of these trials they were considered encouraging, and the figures are given now so that later results may be compared with them. Many improvements have been made in the construction and working of the gas plant since it was first introduced, but the average composition of the gas remains nearly the same, as will be seen from the following analyses by various chemists :—

[1] *Proceedings Inst. C.E.*, 1882, vol. lxxiii. p. 315.

[2] Report of Brit. Assoc., 1881.

[3] Official Report of Smoke Abatement Committee, 1882, p. 113.

TABLE VIII.—COMPOSITION OF GAS (PER CENT. BY VOLUME).

Date.	B.H.P. of Producer.	Hydrogen.	Hydrocarbons.	Carbon monoxide.	Carbon dioxide.	Oxygen.	Nitrogen, etc.	Calories per cubic meter.	Cubic meters produced per kilo of anthracite consumed.	Authority.
1883	8	18·73	0·62	25·07	6·57	0·03	48·98	1420	5·0	Prof. W. Foster, F.C.S.
1889	60	17·0	2·0	23·0	6·0	—	52·0	1420	5·02	Mr. F. Uppenborn, Munich.
1890	40	16·67	—	27·5	8·40	0·90	46·73	1360	4·74	Dr. C. Monaco, Turin.
1890	10	24·0	—	22·5	7·5	—	46·0	—	—	Dr. Langer, London.
1894	120	16·5	1·0	25·4	4·8	1·2	51·1	1384	5·34	Prof. A. Witz, Lille.
1897	40	19·8	1·3	23·8	6·3	—	48·8	1463	5·04	Mr. G. C. Jones, F.C.S.
1898	250	15·3	1·4	27·6	3·9	—	51·8	1451	5·07	" " "
1898	300	17·5	2·1	26·5	4·4	—	49·5	1552	4·88	" " "
Average		18·19	1·40	25·17	5·98	—	49·36	1432	5·01	

It was thought that with a large producer, containing a great mass of fuel at a high temperature, the percentage of hydrogen might be increased without increasing that of the carbon dioxide. On comparing the first and the last two of the analyses in Table VIII. it will be seen that this supposition was not borne out; and it may be assumed that with anthracite of equally good quality the composition of the gas is about the same with a small producer as with a large one, provided the producers are properly proportioned and the other working conditions are as favourable for the one as for the other. In the trial of 1881 the consumption of semi-water-gas was fully five times as great per horse-power as would have been the case with ordinary town gas. By calculation, however, the calorific power of 1 c.m. of an average sample of the semi-water-gas was 1432 calories, or 161 Brit. T.U. per c. ft., while that of 1 c.m. of ordinary 16 candlepower town lighting gas was 5693 calories, or 639·9 Brit. T.U. per c. ft. Tests made with a calorimeter confirmed these figures approximately, and theoretically the comparative consumption of the two gases to get the same power in an engine was as 3·98 : 1. From this it is evident that as long as practice required fully 5 volumes to one the weaker gas was not being used to the best advantage. At the present time, the right treatment of semi-water-gas is better understood, and many important modifications have been made in gas-engines, so that the heat efficiency of an engine working with this gas approximates to that of an engine working with ordinary town gas, and it is now necessary to use only about 4 volumes of good semi-water-gas for one of ordinary town gas. On this point, therefore, theory and practice are now fairly in accord.

The improvements referred to were due in large measure to the better understanding of the thermodynamic problems involved. At first the makers of gas-engines sought improvements almost exclusively in mechanical devices, and less attention than the subject deserved was given to the behaviour of different kinds of gas under the varying conditions of temperature and pressure which must necessarily prevail in the cylinder before and after each explosion. In this country it was Mr. Dugald Clerk who first thoroughly investigated the subject as a chemist and physicist, and his published writings have led to a better understanding of the somewhat complicated and difficult problems involved. With steam power, it is one thing to make steam in a boiler, it is another to make the best use of it in an engine; so with gas power, it is comparatively easy to make gas in a producer but to use it to advantage in an engine is another matter altogether. It will therefore be instructive to review briefly the changes made in the engine which have raised the efficiency of the combination, although the composition of the gas itself has not been appreciably altered.

The Otto engine tested in 1881 had a compression of only 35 lbs. per square inch, and a typical indicator diagram is given in Fig. 26. It was soon ascertained that a higher compression would be better, but at that time slide-valves were used to regulate the ignition as well as the admission of the charge, and a high compression would have caused excessive friction for the valves. For various reasons these troublesome valves were retained for several years, but when tube-igniters were adopted and slide-valves were abandoned a higher compression was used. In the accompanying diagram (Fig. 27) an attempt is made to represent approximately a charge of producer gas and air about to enter the compression space in the cylinder of an early Otto engine, this space being filled with residual products of combustion from the previous charge, left in the cylinder at the end of the exhaust stroke. In this figure the inner cone represents the producer gas, and the outer cone represents air in the proportion of 2 volumes of air to 1 of gas. The dots indicate the combustible part, and the crosses the incombustible part, of the producer gas, the latter being assumed to contain about 50 per cent. of combustible gases, the remainder being nitrogen and carbon dioxide. The circles show the oxygen in the air, and the crosses the nitrogen. It is not possible to show in a diagram what actually occurred during the admission and compression of the charge, but the figure will assist the reader to realise the relative proportions of gas, air, and products of combustion which had to be mixed together. It will also serve to show how difficult it was for the molecules of oxygen

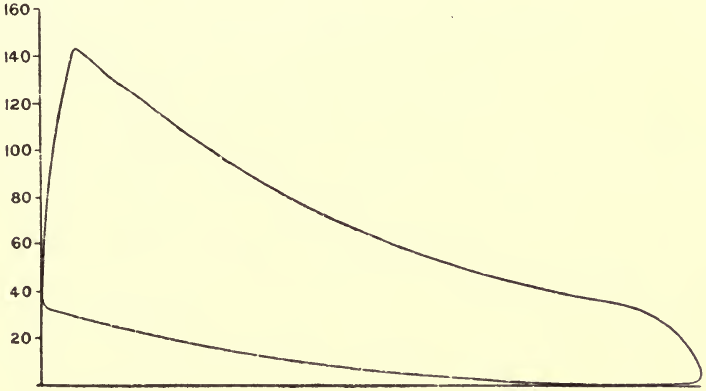

Fig. 26.—Typical indicator diagram with producer gas in 1881.

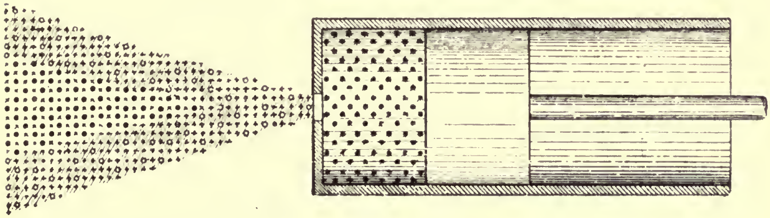

Fig. 27.—Diagram showing charge of producer gas and air about to enter cylinder of early Otto engine.

to reach the combustible gases, surrounded as they were with inert nitrogen and products of combustion. In the first place, before the charge entered the cylinder, it was as though there were two contending parties, four-fifths of one party (the atmospheric nitrogen) endeavouring to prevent the remaining fifth (oxygen) from joining half the members of the other party (the combustible gases), the other half of which was opposed to the union. When the charge of gas and air entered the cylinder it was mixed with a considerable volume of residual products, and the combination of the oxygen with the combustible gases was rendered still more difficult. Apart from these difficulties, there was the fact that carbon monoxide is slow to ignite compared with hydrogen. Hence more than half the combustible constituents of producer gas are rather slow to ignite. One fairly obvious improvement, so far as the gas was concerned, was to remove or scavenge out the residual products before admitting a new charge. To put this to a practical test the makers of the Otto engine, in 1881, fitted a small one with a pump which delivered air into the compression space while the exhaust was open, so as to remove the products and displace them by air. The engine could work with or without the pump, and Fig. 28 shows two typical diagrams taken on the same day, with gas of the same quality. The smaller diagram represents the non-scavenging effect

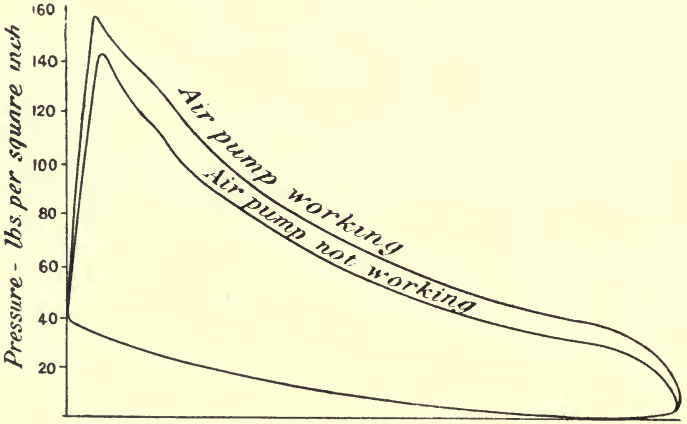

Fig. 28.—Diagrams with and without air pump.

when the pump was not working, and gave a mean pressure of 57·8 lbs. per square inch. The larger diagram superposed shows the effect after scavenging, when the pump was working, and gave a mean pressure of 68·5 lbs. per square inch, or an increase of 18½ per cent. The fact that the exhaust products in the compression space were removed and displaced by air doubtless assisted the combustion of the gas; at the same time it allowed more gas to enter the cylinder so that there was a richer charge, and this to a large extent explains the increase in the mean pressure. In modern engines the compression space is much smaller in proportion to the volume of the cylinder than in the engine of 1881, and the increase of mean pressure due to scavenging is therefore not so great as in the example quoted. But apart from these considerations there is no doubt that it is especially advantageous for a comparatively weak gas, such as producer gas, not to be diluted with exhaust products. Against this improvement there was the extra friction due to the pump, and in the small engine of that date it was rather serious. Besides this, a further complication was introduced in the engine, and this added to the cost of construction, so that the makers were not in favour of the change. In the early Clerk engine the exhaust products were removed, and the inventor of it has always held that scavenging for producer gas is beneficial. Even the inventor of the Otto engine admitted that it was bad for a weak gas to be diluted with products of combustion. In the specification of a patent granted to Dr. Otto, dated January 4th, 1881, these words occur: "The products of combustion do not materially interfere with the combustion of the following charge if the gas employed is of a very inflammable character, such as coal-gas; but when gas of less inflammable character is used, such as carbonic oxide, it is of advantage to remove the said products more or less completely." Later, the manager of the German Otto Engine Works made a still greater admission, and in 1892 he wrote to Mr. Dowson as follows: "In all cases, and especially where weak gas is used, the expulsion of the products of combustion is an advantage; a larger quantity of heat will then be converted into work, and consequently the power developed by the engine will be increased."

Incidentally, scavenging has other advantages. For instance, the mixture of gas and air entering the cylinder is heated and expanded by the products of combustion from the previous explosion, so that the density and strength of each charge is somewhat diminished, a fact to which attention was called long ago by Profs. Ayrton and Perry.[1] Scavenging reduces the temperature of the explosive mixture during the suction stroke, and this not only increases the density of the charge but also tends to prevent pre-ignition. A further point is that if a weak charge enters the cylinder it may burn so slowly that part of the flame may remain in the compression chamber after the exhaust, and may ignite the succeeding charge during the suction stroke while the valves are open. This again would be impossible if all the hot products and flame were scavenged out, especially if a little air were admitted in front of the new charge.

Mr. Atkinson introduced an ingenious method of scavenging without a pump, but it entailed certain drawbacks. It is, however, generally recognised that if scavenging could be adopted without serious complication it would be an advantage, especially in large engines and in engines working with producer gas or other gases of low calorific power; but notwithstanding all the opinions in favour of scavenging, comparatively few engines are made with this provision. The majority of gas-engine makers consider that it is simplest and best to have a reduced compression space and a high compression without scavenging. In steam-engines the greatest care is taken to convert as much as possible of the heat energy of the working fluid into work, and undoubtedly the same should be done in a gas-engine which is to work with producer gas.

This discussion may be thought to be somewhat of a digression, as scavenging has not been generally adopted and therefore cannot have contributed to the improved efficiency of the majority of gas-engines working with producer gas. But the attention drawn to the subject has not been without its influence; indirectly, it has helped to bring about the adoption of a higher pressure for the compression of the charge, and this of itself has notably raised the heat efficiency of the engine, and has reduced the consumption of gas per H.P. In his James Forrest lecture at

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[1] "The Gas-engine Indicator Diagram," *Philosophical Magazine*, July, 1884.

the Institution of Civil Engineers (1904), Mr. Dugald Clerk discussed this in detail, and as a general result he pointed out that in 1882 the heat converted into indicated work was only 16 per cent. of the total heat given to the engine, whereas in 1900 it had risen to fully 30 per cent.

Since 1881 the speed of gas-engines has been increased, and the tendency is to raise the speed rather than to lower it, especially for electrical work. Shorter intervals between the explosions, and therefore between the impulses, naturally lessen the variations in speed, and a quick-running engine is of smaller dimensions for a given power.

In the best engines of to-day about 30 per cent. of the total heat energy of the gas sent into the cylinder is lost by conduction through the walls of the cylinder. In 1882 this loss was about 50 per cent. On the other hand, the loss of heat through the exhaust has not been reduced; on the contrary, its tendency has been to rise, and it is now about 40 per cent. It is a striking fact that the exhaust of a gas-engine often leaves the cylinder at a pressure little under that of the steam pressure used in old times for driving a steam-engine. It is, however, reasonable to expect that in the process of evolution the gas-engine will be further modified and improved; indeed, what Mr. Clerk has aptly termed its present "ratio of imperfection" may be considered as encouraging. If, notwithstanding its defects, it has done so well already, how much better will it be when these defects, or a considerable portion of them, have been remedied?

Numerous tests to determine the fuel consumption per H.P. have been made by well-known authorities, such as Mons. Mathot in Belgium[1]; Prof. Witz in France[2]; Profs. Schottler,[3] Meyer, and Slaby in Germany; Mr. Dugald Clerk[4] and Prof. Burstall in England. The general results show that when a steam-jet plant is used for making the gas a modern gas-engine of good design consumes about 450 grams (about 1 lb.) of fuel per B.H.P.-hour, including the fuel burnt in the boiler to raise the steam required. This is a great improvement on the fuel consumption of the first small engine worked with producer gas mentioned on p. 98, and

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[1] "Moteurs à Gaz."

[2] "Moteurs à Gaz." Paris.

[3] "Die Gasmachine." Brunswick.

[4] "The Gas and Oil Engine." Longmans.

this improvement is not due to any appreciable increase in the calorific power of the gas, but to the various modifications and adjustments of the engine to which we have referred. A further reduction in the fuel consumption is effected when the steam is generated in the gas producer or by the sensible heat of the gas after it has left the producer. This is dealt with in Chapter VII. on Suction Plants.

For engine work it is important that the temperature of the gas when it reaches the engine should be about the same as that of the atmosphere. This is desirable, because it renders the gas more dense so that a given volume yields a larger proportion of heat energy, and consequently develops more power when it is exploded. For practical reasons too, it is objectionable to have moisture deposited from the gas in the pipes and passages near the engine, and to prevent this the gas should leave the plant at the atmospheric temperature. There can then be no further lowering of temperature accompanied by the condensation of a further portion of water-vapour from the gas. This is especially important now that magneto igniters are replacing tube igniters, as there is a tendency for moisture to collect on the terminals after the engine has been standing and is cool. If this occurs it gives trouble when the engine is to be started, as the current is short-circuited and the spark fails. This question of moisture is, however, not always understood, and we venture to give a few explanations as to the cause of its presence and the best way of removing an excess.

We may assume that after passing through water or through wet coke in the scrubbers the gas will be saturated with moisture at whatever temperature it may be. We have found by testing that this is actually the case, so that a cubic meter of gas contains exactly the same quantity of water-vapour as a cubic meter of saturated air at the same temperature. It follows, therefore, that as the gas at any given temperature contains sufficient water-vapour for saturation the quantity of water-vapour in the gas will be less at a lower temperature, and on being cooled any excess of water-vapour beyond that required for saturation will be condensed. If, therefore, warm gas enters a cold engine, some of the water-vapour carried with it will be thrown out by condensation and will be deposited. A knowledge of the temperature of the gas in the pipe near the engine enables us to calculate the amount of water-vapour required to saturate the gas at that point, but it will not enable us to determine the amount of condensed water which may be held in suspension, over and above the amount of water present in the form of vapour. If we wish to determine the total content of water-vapour and of condensed moisture held in suspension it is necessary to pass some of the gas through a chemical absorbent, such as calcium chloride or concentrated sulphuric acid. To remove the condensed moisture from the gas before it reaches the engine it is best to pass the gas through a filter of sawdust or other suitable material. This will not affect the amount of uncondensed water-vapour in the gas, but it will to a great extent arrest the passage of condensed moisture held in suspension.

We have had to deal with a case where the temperature of the water used in the scrubbers was considerably lower than that of the surrounding air, and the temperature of the gas as it reached the engine was below that of the air, yet moisture was deposited in the cylinder of the engine and on the terminals of the igniter. It was evidently a case where condensed moisture was carried along by the gas, and the trouble was got over by passing the gas through a thick bed of sawdust.

Although the gas might not contain more water-vapour than is necessary for saturation, condensed moisture might be deposited at any point where there was a sudden reduction of pressure in the gas, because this sudden reduction of pressure would cause a lowering of temperature. It might be supposed that this would occur as the gas enters the cylinder on the suction stroke, when there is a lowering of pressure; but this is only momentary and does not give time for the deposition of moisture. Moreover, as soon as the gas enters the engine (after it has been working) it comes in contact with warm surfaces, which have a contrary effect. It may sometimes happen, when an engine has been standing and has been cooled by water colder than the gas, that when the latter comes in contact with the metal surfaces its temperature is lowered; and there is then some deposition of condensed moisture.

The hot gas which leaves the producer can be cooled by passing it through pipes and coolers exposed to the air; but as the gas is usually consumed as quickly as it is made, and as its volume is considerable—say 2·1 to 2·25 c.m. (75 to 80 cub. ft.) per B.H.P.-hour—this process alone would be too slow, and the cooling apparatus would be too large and too costly. It is therefore usual to pass the gas through a water-seal, and through one or more scrubbers containing wetted coke, as shown in Fig. 29.

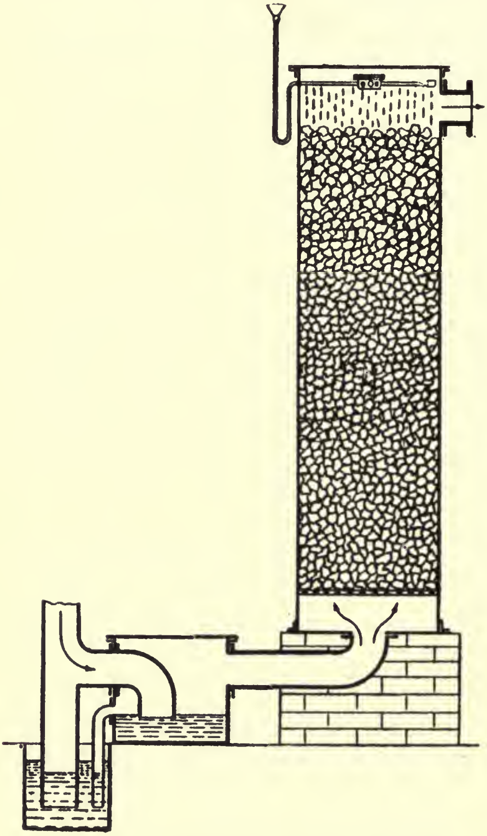

Fig. 29.—Hydraulic seal and coke scrubber.

In an anthracite or coke plant the quantity of water required for cooling and cleaning the gas should be about 3 liters ($\frac{2}{3}$ gallon) per B.H.P.-hour. Sometimes, in order to reduce the first cost of the plant, smaller scrubbers are used than is desirable, and then the consumption of water is necessarily higher.

In a well-designed steam-jet plant the weight of steam decomposed is about 75 per cent. of the weight of anthracite consumed in the producer. The total quantity of water required for the steam and for the cooling and cleaning of the gas may therefore be put at about 3·3 liters ($\frac{3}{4}$ gallon) per B.H.P.-hour. Water is also required for cooling the cylinder, etc., of the gas-engine, but this has no connection with the gas plant; the quantity is, however, insignificant if there is a cooling tank with a flow and return from the cylinder.

On referring to Table VIII., it will be seen that an average of about 18 per cent. of hydrogen was produced, with the accompaniment of an average of 6 per cent. of carbon dioxide, and it has been supposed that there cannot be a gain in increasing the hydrogen if it involves a proportionate increase in the carbon dioxide. This question has already been dealt with in its theoretical aspects in Chapters I. and II., and it may be well to consider it briefly from the practical side. By way of example we will therefore suppose that there is a sample of gas having the following composition :—

Hydrogen	15	per cent.	by volume.
Carbon monoxide	27	„	„
Carbon dioxide	4	„	„
Nitrogen, etc.	54	„	„

The calorific power of this gas at standard temperature and pressure would be 1289 calories per cubic meter; and if the hydrogen were increased 5 per cent. experience shows that a gas of about the following composition would probably result :—

Hydrogen	20·0	per cent.	by volume.
Carbon monoxide	22·8	„	„
Carbon dioxide	6·5	„	„
Nitrogen, etc.	50·7	„	„

This would have a calorific power of 1314 calories per cubic meter, and at first sight there would appear to be little gain in raising the percentage of hydrogen, if there were a simultaneous rise in the carbon dioxide; but with a comparatively low compression in the cylinder (as was formerly the case) a certain increase of hydrogen assisted the ignition of the charge in the cylinder of the engine, the carbon monoxide being comparatively slow to ignite. This consideration is of less importance now that the pressure of compression has been raised, as the ignition is satisfactory when there is not more than 15 per cent. of hydrogen in the gas, or even less. There is, however, a further point to consider in connection with hydrogen, namely, its bearing on the question of pre-ignition. We have seen that the heat efficiency of an engine is raised by an increase in the pressure of compression, but that the compression which can be used in practice is limited by the necessity of avoiding pre-ignition. When a gas is compressed as in a gas-engine cylinder its temperature is raised considerably, but it is essential that the temperature of compression should be less than the ignition temperature of the charge. Exact data are wanting for the ignition temperature of mixtures of various gases with air, but Mr. Clerk says, "It is known in a general way that gases which contain a large proportion of hydrogen are ignited at a comparatively low temperature," and that "compression can be carried very much farther with weak gas of the producer type, such as blast-furnace gas, than with very inflammable gases, such as town gas or natural gas."

It should also be remembered that it is not so much the percentage of hydrogen in the gas which is important as the percentage of hydrogen in the charge of gas and air introduced into the cylinder; so that a town gas containing 50 per cent. of hydrogen is not so much more liable to pre-ignition than a producer gas containing 15 per cent. as these figures would seem at first sight to indicate. If, however, we take two examples of producer gas, one containing 15 per cent. of carbon monoxide and 25 per cent. of hydrogen, the other containing 25 per cent. of carbon monoxide and 15 per cent. of hydrogen, the quantity of air required for combustion is the same in each case. Therefore in the cylinder of the engine there will be 25 parts of hydrogen in the first case and only 15 parts in the second; and in this proportion the charge in the former will be more liable to pre-ignition than in the latter

It is true that when gases are fired in the cylinder of an engine hydrogen explodes more readily than carbon monoxide, and its combustion during the explosion is more complete; but the heat lost in the exhaust is increased, owing to the latent heat of the steam produced. On the other hand, carbon monoxide explodes less readily, and its complete combustion is less certain; but there is no loss from latent heat.

Whatever the composition of the producer gas may be it is desirable that there should be a good igniter. The old-fashioned slide-valves with ignition ports were certainly troublesome, and the ignition tubes afterwards used were much more satisfactory;

moreover, they could be heated by a jet of producer gas, so that an installation could be entirely independent of town gas and an engine could be worked in places where there was no town gas at all. More recently magneto igniters have found favour, and, as we shall see later on, they are essential for suction plants in places where there is no town gas with which to heat a tube igniter. The great point about the ignition is that it should be prompt and sure, especially for a comparatively weak gas such as producer gas.

In Chapter XII. we shall deal fully with the fuels suitable for producer gas for various purposes, and Chapter IX. will be devoted to the production of gas from bituminous coal for engine work. For gas power, anthracite or coke is generally used for plants up to about 200 B.H.P., and for larger sizes in places where the cost of bituminous coal is not much less than that of the other fuels. From the practical point of view we may say generally that anthracite is rather better to work with than coke of average quality. Both give about the same heat efficiency; but there is usually more ash in the coke, and consequently there is more trouble with clinker. Also the yield of gas may be taken at about 10 to 20 per cent. less with coke than with anthracite; consequently, from 10 to 20 per cent. more coke must be used for a given output. It also takes rather longer to get the gas plant in working order for making good gas when coke is used. It follows, therefore, that when the two fuels cost about the same it is better to use anthracite; but that when coke is cheaper it is better to use it, provided it is well carbonised and does not contain more than 10 to 12 per cent. of ash.

CHAPTER VII

SUCTION PLANTS

We have seen that in some of the early gas producers used for furnace work air was drawn into the producer by suction, instead of being forced in under pressure, as in producers of later date. In recent years the idea of working the producer by suction, instead of by air at pressure, has been reverted to, chiefly in connection with gas-engines. As early as 1862 Dr. Jacques Arbos, of Barcelona, patented a combination of gas plant and gas engine in which the latter drew gas direct from the producer. It was not a very practical arrangement, and the charge of gas and air was not compressed before ignition, but it deserves to be mentioned as one of the early suction plants devised. The first to give effect to this idea in a practical way in a compression engine was M. Léon Bénier, of Paris. His first patent was in 1891, and he afterwards took out others; the gas plant shown in Fig. 30 represents what was first used for practical work (1894) in conjunction with the special engine shown in Fig. 31. In the former figure, **A** is the gas producer; **B** the feeding hopper; **C** a revolving grate containing water; **D** a chamber to receive steam produced in **C**; **D′** is a chamber open at the bottom to receive steam from **D** and allow it to expand to atmospheric pressure; **E** the air inlet; **E′** a passage for steam from chamber **D′**; **F** a mixing chamber for steam and air at atmospheric pressure; **G** the inner casing of gas producer; **H** an annular space for steam and air to pass from **F** to the bottom of fire, the steam and air being heated on the way; **I, I** an annular space for hot gas from the producer; **J** a cylinder with water inside; **K** an inner cylinder, of which the lower end is dipped in water in **J** so as to form a washer for the gas, with an overflow leading to the tank **L**; **N** a chamber to receive gas, with outlet **O** at the top.

The engine had a suction pump by the side of the motor cylinder, as shown in Fig. 31, and this pump was connected by a pipe with

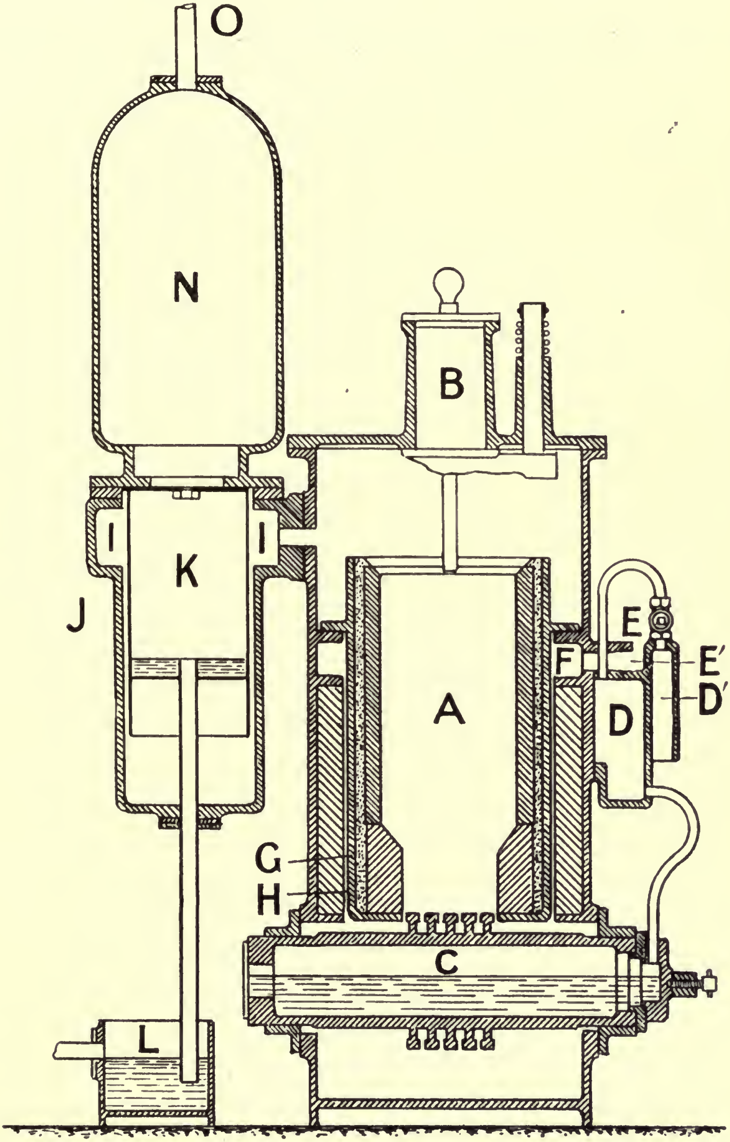

Fig. 30.—Bénier early suction plant.

the outlet **O** in Fig. 30. As soon as the fire was lighted it was blown up with a hand-power fan, and when the gas was good enough to work the engine, the latter was started. The pump on the engine then drew gas from the producer and forced it into the motor cylinder. This suction of gas from the producer lowered the pressure in the latter, and as a consequence air from the outside (at atmospheric pressure) flowed in through the inlet **E**. The steam or water-vapour formed in **C** mixed with the air before the latter entered the fuel column, and both steam and air were drawn together into the fire. By suitable adjustments, the volume of air drawn in varied with the rate at which gas was consumed in the engine; in other words, the rate of producing the gas was governed automatically by the engine itself, and both the gasholder and the independent boiler were dispensed with altogether. As this plant and those of which it is the type work by suction they are now generally known as *suction plants,* to distinguish them from pressure plants worked by air at pressure.

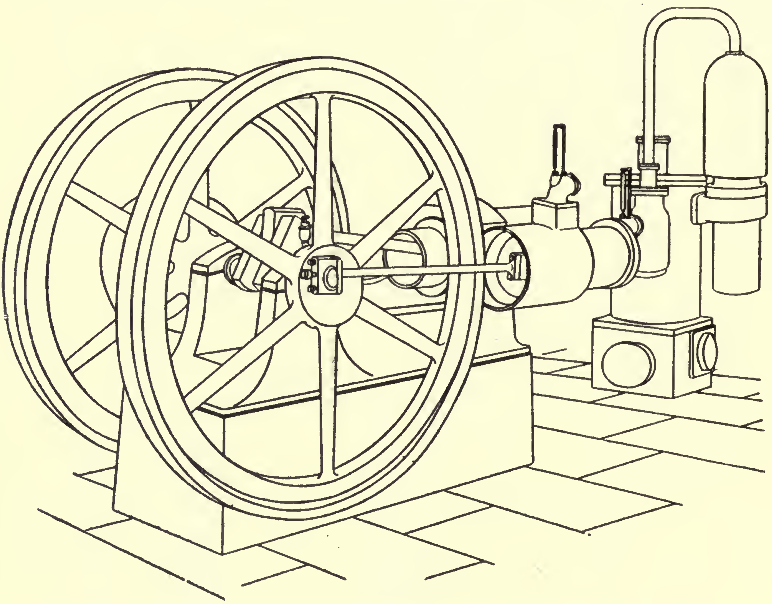

Fig. 31.—Bénier gas engine and suction plant.

Prof. Aimé Witz, of Lille, tested M. Bénier's combination of gas plant and engine, made to serve about 15 B.H.P. The first trial[1] was with English anthracite of good quality, and the calorific power of the gas was 1149 calories per cubic meter, or 129 Brit. T.U. per cubic foot. The engine developed 27·6 I.H.P., but only 14·59 B.H.P.; while the consumption of anthracite was 714 grams, or 1·57 lb. per B.H.P.-hour. A second trial was made with ordinary gas coke in the producer, and the calorific power of the gas was then as low as 1035 calories per cubic meter, or 116 Brit. T.U. per cubic foot. The engine developed 14·7 B.H.P., and the consumption of coke was 752 grams, or 1·66 lb. per B.H.P.-hour. These results were with a full load on the engine, and it is probable that the gas would have been still weaker if the load had been much reduced, as the temperature of the fuel most favourable for making the gas would probably not have been maintained.

At that date (1895) the consumption of fuel in a pressure plant, *i.e.* the consumption of anthracite in the producer and of coke in the boiler, was guaranteed by different makers not to exceed a total of 450 to 500 grams (1 to 1·1 lb.) per B.H.P.-hour. There was, therefore, a considerable loss of fuel by using the suction plant of that date, notwithstanding the fact that it required no independent boiler, while the amount of fuel consumed in the boiler of the pressure plant usually represented from one-sixth to one-fifth of the total fuel consumed. The gas was poor in quality compared with that made in a pressure plant, and there were other drawbacks; but the idea was an ingenious one, and it was seen that the working of a gas plant by suction in combination with an engine would have distinct advantages if the practical details could be worked out in a satisfactory manner.

Several engineers gave their attention to the subject, and the next step of importance was to do away with the pump on the engine and to use the suction of the engine itself, *i.e.* the suction caused by the outstroke of the piston in the motor cylinder, to draw gas from the gas plant. This reduced appreciably the loss from friction. Various methods have been devised for producing the steam required and for removing the clinker formed in the

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[1] "Moteurs à Gaz," vol. iii. p. 186; *Encyc. Brit.*, vol. xxviii. p. 606.

producer, as the arrangements adopted by M. Bénier were not satisfactory. He himself recognised this, and his more recent apparatus shows several modifications and improvements in this respect. The production of the steam required to make gas of good quality and to keep the temperature of the fire low enough to prevent the formation of an excessive amount of clinker presents many difficulties. Some makers have a water-vapouriser inside the producer, sometimes near the bottom of the fire, but more often near the top; and they heat it by the fire or by the hot gas which leaves the fire. In some cases both these sources of heat are used. On the other hand, some makers prefer to have the vapouriser outside the producer and to heat it by the sensible heat of the gas after it has left the producer. The latter system has the advantage of cooling the gas more, but the amount of steam raised is less than in the other systems and there is the risk that the gas will not always be hot enough to make the full quantity required. This not only affects the percentage of hydrogen, etc., in the gas, but has an important bearing on the formation of clinker. It is, in fact, essential that there should be a sufficiency of steam; yet this point does not always receive the attention it deserves.

The steam is produced at atmospheric pressure, and to avoid losses by condensation when it mixes with the air drawn into the producer the steam, or the mixture of steam and air, is sometimes superheated by passing it through a chamber heated by the fire in the lower part of the producer. Another method which is adopted is to heat the air supply to the producer by causing it to be drawn through a jacketed space surrounding the body of the producer or the gas outlet pipe. The heating of the air supply by waste heat from the producer has further important advantages; a certain quantity of heat which would otherwise be lost is carried back to the producer, so that more steam can be decomposed and the efficiency of the process improved; when the producer is working at a small output, and the temperature of the fire tends to become too low (*see* p. 148), the hot air supply assists in maintaining the working temperature; and further, the producer starting all cold is sooner brought into its normal working condition. So long as the temperature of the mixture of steam and air entering the fire is below 100° C. the quantity of steam or water vapour in the mixture is limited, not by the quantity produced in the vapouriser, but by the temperature of the mixture; for at temperatures below 100° C. the air can only carry a certain proportion of water vapour (*see* p. 266). The diagram, Fig. 31A, based on the figures given in Table XXVIII., shows the weight of water vapour in 1 kilo. of saturated air at different temperatures. It will be seen that the quantity of water vapour carried with the air is not sufficient unless the temperature is about 70° C. It is therefore important that the producer should be designed so that the mixture of steam and air is heated at least to this temperature before entering the fire, and so that this temperature is reached as soon as possible after starting. The increased tendency to clinkering when a heated air-blast is used may be counteracted by using sufficient steam, and when the air is heated in any of the ways described it is of course all the more important that a sufficient quantity of steam be used with it.

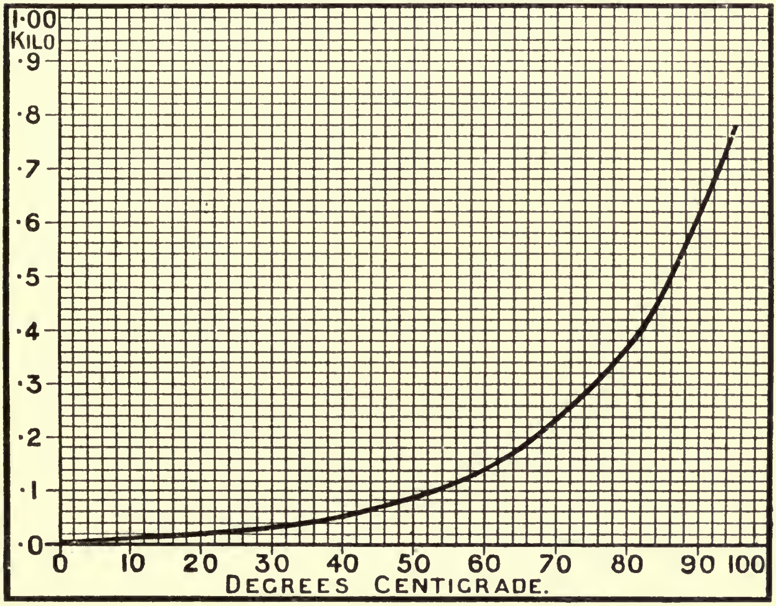

Fig. 31A.—Weight of water vapour in 1 kilo. of saturated air.

Apart from producing a sufficient quantity of steam when the maximum volume of gas is required, there is the further necessity for regulating the quantity of steam drawn into the fire when the load on the engine is variable. It has been supposed that when less gas is produced, *i.e.* when less air is drawn into the fire, the lowering of temperature which follows causes less steam to be produced, and that in this way the quantity of steam produced is proportional to the quantity of gas required. This is only partly true, as actually the temperature of the fire does not vary as quickly as the load on the engine may vary, and although there may be a considerable fall in the load, there is usually heat enough in the fire to produce more steam than is then desirable. If this excess of steam continues, it not only causes an excess of carbon dioxide to be formed, but it damps down the fire. Then, when the load is increased suddenly, the temperature of the fire is not high enough to give effect to the necessary reactions, and the gas is not good enough to develop the power required. Some makers of suction plants try to get over this difficulty by having regulating valves worked by the engine, by means of which the admission of steam to the fire is governed by the engine. Some merely allow a vent in the vapouriser for the excess of steam to escape when the load is reduced, some make no special provision at all; while Mr. Dowson and others have used the suction of the engine to draw water into the vapouriser in very small quantities, just enough at each suction stroke to give the steam required for the quantity of gas to be consumed. This has answered well, and as a result the engine governs not only the admission of air to the producer but also the admission of water to be converted into steam. This can only be done provided the vapouriser flashes the water into steam; if the vapouriser holds a body of water, as in a boiler, steam is given off continuously, and although there might be a governing of the feed-water the quantity of steam produced would not be governed.

We cannot emphasise too strongly the importance of providing steam enough, and of regulating the quantity to suit all the variations in the volume of gas produced.

We will now give some typical examples of the numerous suction plants which are made in this and other countries. Fig. 32

represents the plant made by M. Delassue, of Paris; the vapouriser is below and around the lower part of the fire, and

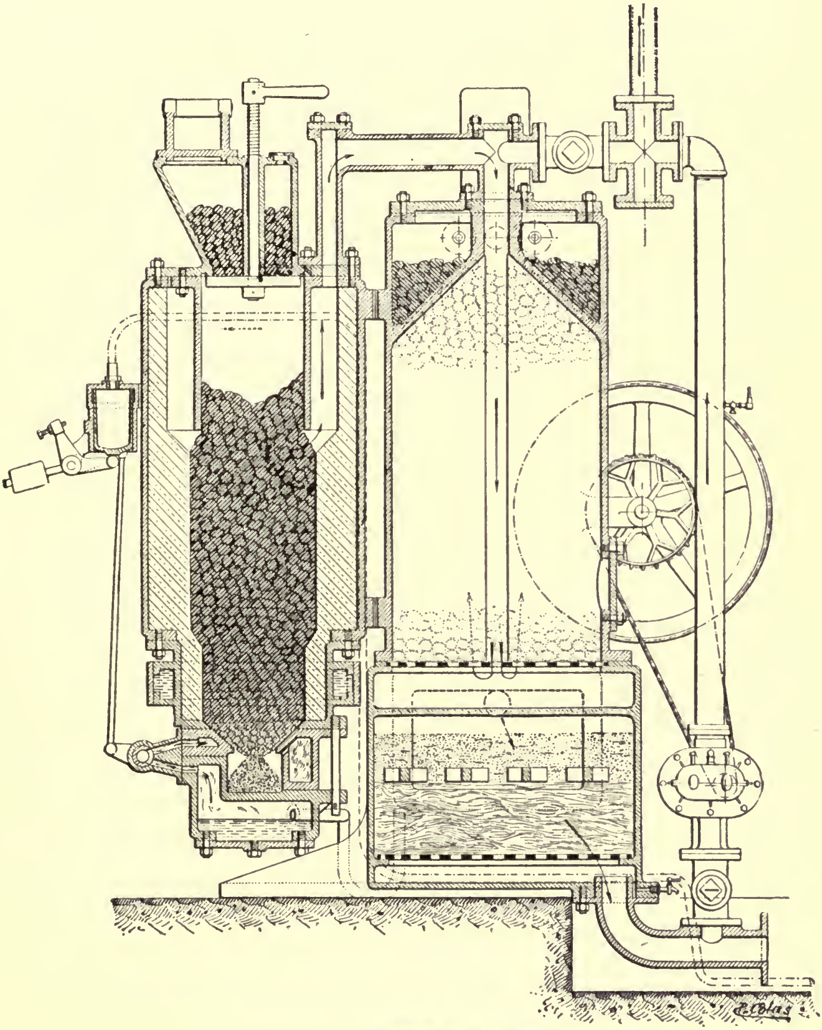

Fig. 32.—Delassue suction plant.

the admission of steam to the fire is governed by a valve actuated by the engine, so that steam is admitted during the suction stroke only, any excess being allowed to escape into the air. In this way it is claimed that the quantity of steam converted into gas is always in the proportion required by the engine under any variation of load. The firebox at the bottom of the producer has an opening to admit the air required, and there is a suction fan on the outlet of the plant to draw up the fire at starting, instead of the usual blower. When the gas is good enough to serve the engine, it passes down a central pipe in the coke scrubber, then upwards through coke, and finally through sawdust in the base of the scrubber, to the outlet.

In Fig. 33 we represent the plant made by MM. Fétu-Defize, of Liège, Belgium; in this, **A** is the producer, **B** a scrubber, and **P** a washer. The fuel is introduced through the feeding hopper **T**; the vapouriser **V** is at the top of the producer. When the engine takes gas, it draws in air at **F**, and this air mixes with the steam in the vapouriser; the mixture of steam and air then passes through the chamber **E**, and is heated by contact with the pipe **G**, through which the hot gas passes. The steam and air afterwards pass through the chamber **C**, which surrounds the lower part of the fire, and are then discharged through **O** into the space under the firegrate. The gas from the producer passes through **G** into the scrubber **B**, and then through the washer **P**. No provision other than the escape of steam at **F** is made for regulating the proportion of steam for varying loads.

In Fig. 34 we illustrate the plant made by Herr Julius Pintsch, of Berlin. In this the gas producer has a special feeding hopper which swings, and an independent vapouriser outside; there are a coke scrubber, a purifier, and a pressure governor. When gas is sucked by the engine the bell of the governor falls, and after the suction the bell is made to rise by the spring on the top. The object of this is to equalise the pressure of the gas in the main leading to the engine, and the advantage is probably more marked when there are two or more engines served by one gas plant.

In Fig. 35 we show the suction plant made by Messrs. Crossley Brothers, Ltd., of Manchester. In this the vapouriser is at the top of the producer, and a portion of the air required is admitted through a cock, which is also used for the escape of any excess of steam produced. The steam and air mix in the vapouriser and pass downwards into a hot chamber surrounding the lower part of the fire, and after passing through this chamber they are discharged under the grate. A further supply of air is admitted at

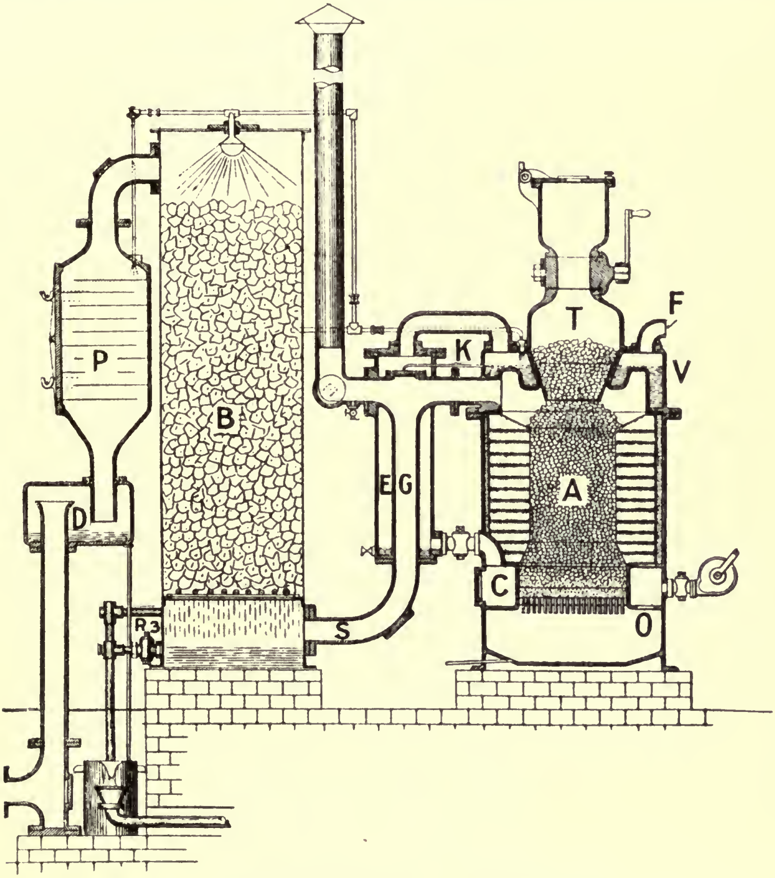

FIG. 33.—Fétu-Defize suction plant.

the base of the producer and is mixed with the steam and air above mentioned. The gas produced passes through two small coke scrubbers in series.

Fig. 36 represents the plant made by Messrs. Watt & Co, of Birmingham. In this, water is vapourised by passing along a spiral trough between the firebrick lining and the outer casing of the producer. The air enters this enclosed space and mixes with the steam on its way to the space under the firegrate. For starting the fire the usual hand-power fan is dispensed with, and instead of this a little fire is kindled in a basket or grid surrounding a portion of the waste pipe. As soon as combustible gas is produced and drawn through the waste pipe it ignites by coming in contact with the little fire just mentioned. This adds to the heat, and

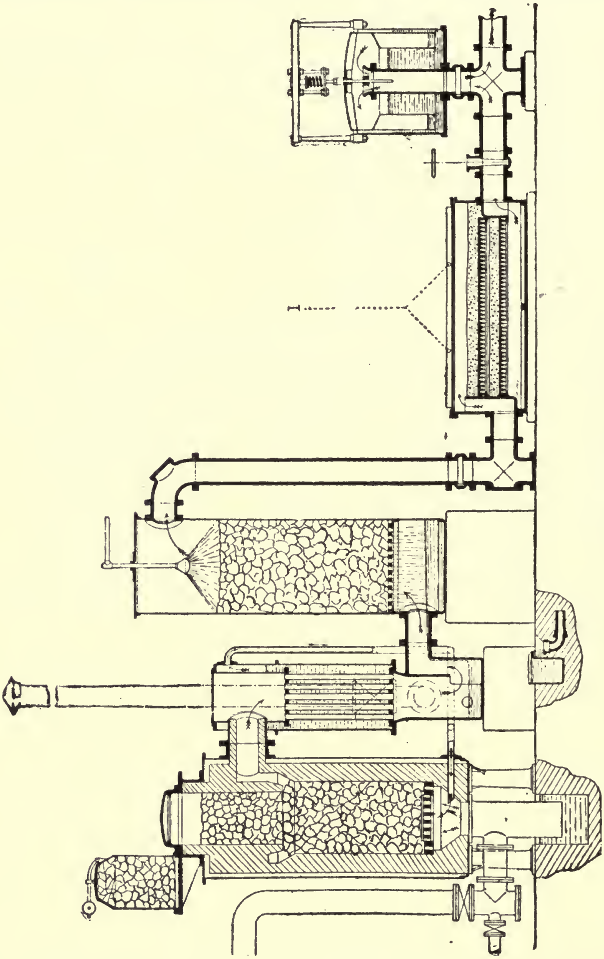

FIG. 34.—Pintsch suction plant.

consequently increases the draught. At the top of the scrubber there is a flexible diaphragm for the purpose of equalising the pressure of the gas between the suctions of the engine. A lever worked by the oscillations of this diaphragm actuates a valve in the water-supply pipe, so that a certain quantity of water is supplied to the vapouriser every time a charge of gas is drawn in by the engine.

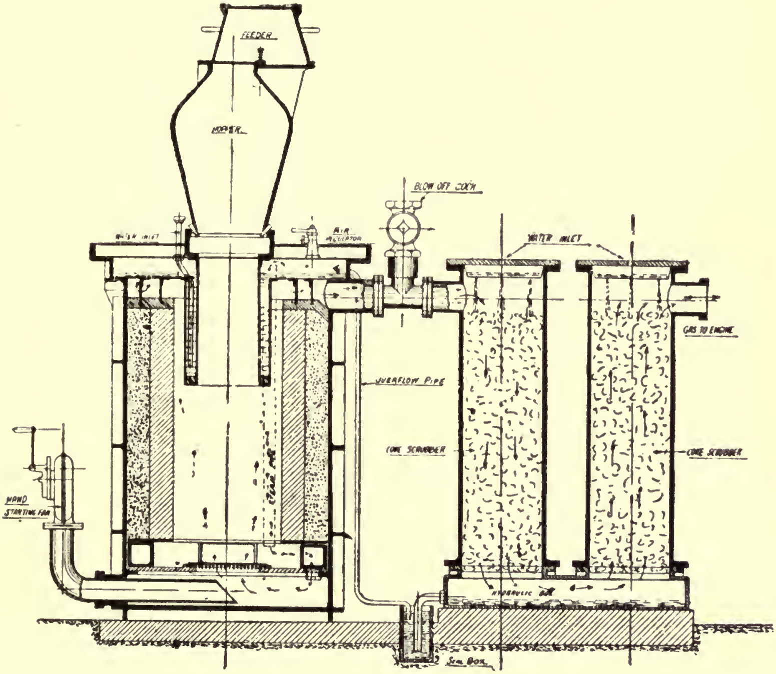

FIG. 35.—Crossley suction plant.

Several methods are used to regulate the supply of steam in accordance with the load on the engine, and the following may be taken as the leading types :—

In the Delassue plant the passage of steam from the vapouriser is controlled by a valve actuated by the engine; the quantity of steam admitted to the fire is thus definitely regulated. In the arrangement shown in Fig. 33, steam is drawn from the vapouriser to the fire at each suction, and when the gas-valve is not opened the steam formed in the vapouriser may escape at the air inlet **F**. Part of the excess of steam, however, displaces air from the steam-space of the vapouriser, and the effect is that at light loads the proportion of steam to air drawn into the fire is greater than at full load. This drawback is met in the Crossley plant by the use of an additional air inlet at the base of the producer, so that at light loads only a small proportion of the air is drawn through the steam space of the vapouriser. In Fig. 36, the supply of water to the vapouriser is regulated in the manner described above; another way of doing this is shown in the plant illustrated in Fig. 37. The water feed-pot **E** has a continuous supply and a constant level overflow, and it forms one limb of a **U**-tube, the other limb being in the vapouriser. Normally the water is just at the level of the open end of the **U**-tube in the vapouriser, and when the sucking action of the engine occurs, a small quantity of water overflows;

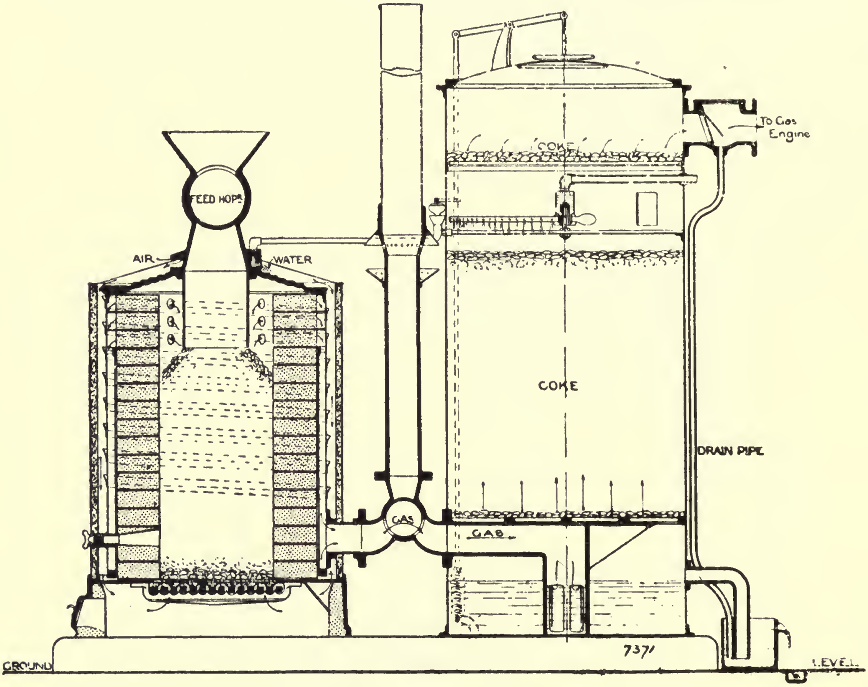

FIG. 36.—Watt suction plant.

the supply of water to the vapouriser is thus in proportion to the number of working strokes made by the engine.

As suction plants are of recent date few complete tests of them have yet been published. There are various records of the horse-power developed, and of the fuel consumed per H.P.-hour, but the subject deserves to be treated more exhaustively.[1] We have made several tests with suction plants designed by Mr. Dowson, and numerous samples of gas made under different conditions of working have been analysed, but we prefer to give the results of tests made by independent investigators. When Mr. Dugald Clerk was preparing his James Forrest lecture for the Institution of Civil Engineers in April, 1904, he was anxious to know the actual

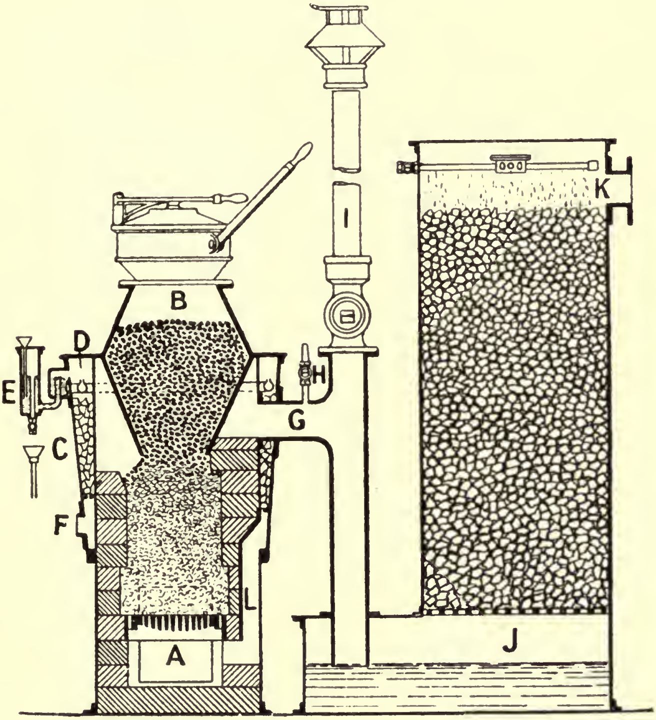

Fig. 37.—Dowson suction plant (30 B.H.P.) tested by Mr. Adam.

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[1] The trials made at Derby for the Royal Agricultural Society are referred to on p. 138.

heat efficiency of a suction plant. Mr. Dowson therefore placed at his disposal two plants of this type, one for 30 B.H.P., the other for 40 B.H.P., as shown in Figs. 37 and 38, and both were rigorously tested on his behalf by Mr. M. A. Adam, B.Sc.[1]

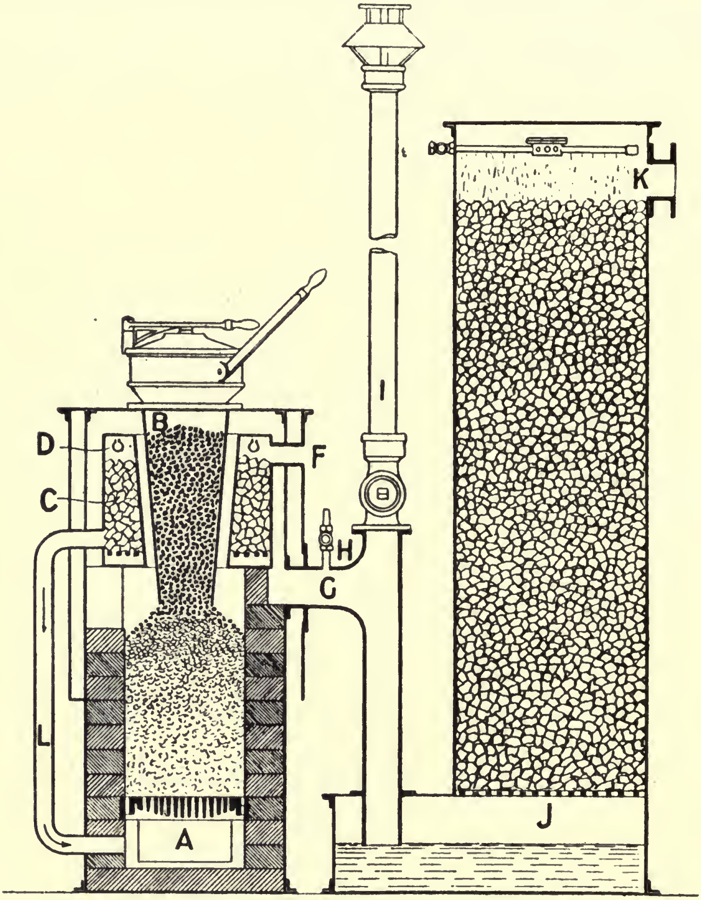

FIG. 38.—Dowson suction plant (40 B.H.P.) tested by Mr. Adam.

In Fig. 37, **A** is the grate on which the fuel rests; **B** is the container holding a store of fuel which is admitted through the hopper and valve at the top; **C** is a chamber filled with loose

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[1] *Proc. Inst. C.E.*, 1904, vol. clviii. p. 320.

pieces of firebrick; **D** is a circular pipe with holes in the top, which receives water from the feed-pot **E**; **F** is the air inlet, and **G** the gas outlet, with test-cock at **H**; **I** is a chimney or waste pipe; **J** is a coke scrubber with water-seal at the bottom; **K** is the gas outlet. There was also a small hand-power fan (not shown in the figure) for blowing up the fire at the start. When the plant is to be worked, a little oily waste and some wood are put on the grate **A**, and the producer is filled with anthracite or coke in small pieces. The feeding hopper is then closed, and the cock on the waste-pipe **I** is opened; the fire is then lighted, through a door on the level of grate **A**; the fan is set in motion, and the products are in the first instance allowed to escape through the pipe **I**. The water-supply is turned on, and as soon as gas will burn well at the test-cock **H**, it is ready for use in the engine; the waste pipe **I** is then closed, and gas is blown off through a waste pipe near the engine until good gas from the producer reaches the gas-cock on the engine. The engine is then started and the fan is stopped. From this time the engine itself draws in the air required for the producer, as well as the water to be vapourised in the chamber **C**, the mixture of steam and air passing downwards from **C**, through **L** to the underside of the grate **A**.

In Fig. 38 similar reference letters are given to the various parts of the apparatus, but it will be noticed that the details of construction, especially of the vapouriser, etc., are somewhat different. The process of making the gas is, however, the same in both the plants.

The fuel used in Mr. Adam's trials was the ordinary commercial quality of anthracite peas from one of the well known collieries in South Wales, as used regularly at the works of the makers of the gas plants.

On each occasion the plant was worked fully eight consecutive hours, the producer being started cold. Samples of the anthracite were taken by Mr. Adam, and were analysed by Mr. Bertram Blount, F.I.C. Gas for sampling was drawn off continuously by an aspirator during the whole of the tests, and samples were taken every half-hour by Mr. Horatio Ballantyne, F.I.C., and were afterwards analysed by him. In the 30 H.P. trial, half-hourly determinations of the calorific power of the gas were also made by Mr. Adam with a Junkers calorimeter. All the thermometers used were corrected by thermometers standardised at Kew, and every precaution was taken to avoid the possibility of error.

To start the fire in each producer the small hand-power fan already described was used, and in about ten minutes after lighting the fire the gas was good enough to start a gas-engine, as shown by a flame at the test-cock **H**. As soon as the gas was good enough the hand-power blower was stopped and a power-driven suction fan was started to draw the gas steadily from the producer. This was taken to represent fairly the action of an engine under constant load drawing gas from the producer, a fan being used instead of a gas-engine so that the gas might be measured and tested accurately. The gas was delivered by the fan under pressure through a new large dry meter into a gasholder; it then passed out through a pipe and was burnt. A diagrammatic view of the testing apparatus used is shown in Fig. 39. In this **A** is the gas-meter; **B** the suction fan; **C** the gasholder; **D** a shut-off valve; **E** the gas outlet; **F** a branch tube conveying gas to the sampling apparatus **G**, in which **H** is the outlet for drawing off samples; **I** is another branch tube conveying gas to the testing meter **J** and calorimeter **K**.

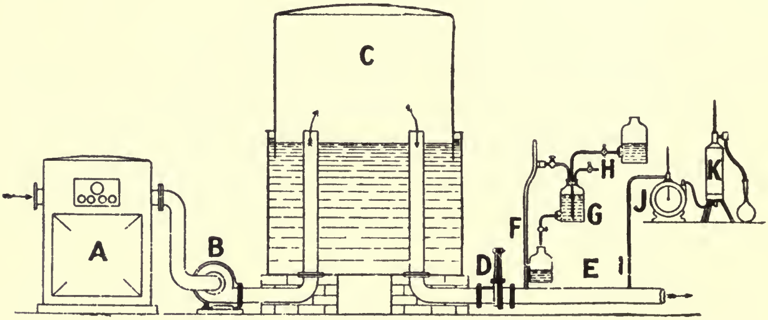

Fig. 39.—Diagram of testing apparatus.

The heat efficiency of each plant was taken in two ways. In the first the whole test from start to finish was included, *i.e.* a start was made with the producer and other apparatus all cold. In the second the test began after the plant had worked two hours, so as to determine the heat efficiency of a plant working continuously after it had been fairly started. For this test the fuel was made up to a definite level at the end of the first two hours, and again at the end of eight hours, so that the fuel actually consumed during the last six hours could be ascertained, after making due allowance for the clinker and ash found in the producer. The general results are given in the following tables, IX. and X., which are based on a table compiled by Mr. Adam:[1]—

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[1] *Proc. Inst. C.E.*, 1904, vol. clviii. p. 322.

TABLE IX.—TRIAL OF 30 B.H.P. SUCTION PLANT WORKING WITH ANTHRACITE.

	FUEL.					GAS.						
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Heat efficiency.	
							By calculation.	By Junker calorimeter.			Lower value.	Higher value.
	Calories per kilo.	Per cent.	Per cent.	Kilos.	Calories.	Per cent by volume.	Calories per cubic meter.		Cubic meters.	Calories.	Per cent.	Per cent
Whole run—cold start.	7955	3·37	3·975	109·48	870,950	H 15·2 CH_4 1·2 CO 21·0 CO_2 8·2 O 0·2 N 54·2	1225	1243	531·90	652,000	70	**75**
Last six hours—hot start.	7955	3·37	3·975	71·94	572,280	H 15·60 CH_4 1·21 CO 21·05 CO_2 8·41 O 0·20 N 53·53	1210	1243	382·88	474,600	77	**83**

TABLE X.—TRIAL OF 40 B.H.P. SUCTION PLANT WORKING WITH ANTHRACITE.

	FUEL.					GAS.						
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Heat efficiency.	
							By calculation.	By Junker calorimeter.			Lower value.	Higher value.
	Calories per kilo.	Per cent.	Per cent.	Kilos.	Calories.	Per cent. by volume.	Calories per cubic meter.		Cubic meters.	Calories.	Per cent.	Per cent.
Whole run—cold start.	7715	3·60	8·76	111·25	858,250	H 15·59 CH_4 1·31 CO 19·05 CO_2 5·93 O 0·79 N 57·33	1180	—	619·82	731,000	79	**85**
Last six hours—hot start.	7715	3·60	8·76	81·65	629,900	H 15·64 CH_4 1·16 CO 20·13 CO_2 6·09 O 0·74 N 56·24	1204	—	473·29	570,000	84	**90**

NOTE.—The above results in British weights and measures, as well as those of Table XI., are given in Tables XXV., XXVI., and XXVII. in Appendix A.

In his report Mr. Adam explained that, "For the sake of convenience of comparison, the efficiencies on the lower heating value[1] are given in addition, but it should be remembered that the loss through condensation of the steam produced by the burning of the hydrogen of the gas is, in reality, a gas-engine loss, and not a producer loss, so that the efficiency on the higher heating value is the true heat efficiency."

It will be seen that the heat efficiency of the 30 B.H.P. plant was 75 per cent. for the whole eight hours' run with a cold start, and 83 per cent. for the six hours' run with a hot start. For the 40 B.H.P. plant it was 85 per cent. with a cold start, and 90 per cent. with a hot start. We are not able to explain precisely why the heat efficiency of the 30 H.P. plant was lower than that of the 40 H.P. plant. Under the mixed conditions which prevail when gas is being made it is hardly possible to measure all the heat losses in detail; but it may be fairly assumed that the principal cause of the lower efficiency of the smaller apparatus was that it had greater cooling surfaces in proportion to the body of fire in the producer and to the volume of gas produced. In the 40 H.P. plant the cooling surfaces were relatively smaller. As a general result the heat efficiencies of these two small plants were certainly satisfactory, and do not leave much room for improvement.

It may be added that during these tests the following quantities of water were used:—

For the vapouriser of 30 B.H.P. plant, about 20 lbs. per hour.
" " 40 " " 30 " "
For the scrubber of 30 " " 380 " "
" " 40 " " 400 " "

The rise of temperature of the scrubber water at the overflow was about 40° C.

It was then arranged that Mr. Larter should make a similar test with small gas-coke in the producer, instead of anthracite. This test was begun the day after Mr. Adam's tests were finished, and precisely the same 40 H.P. gas plant and the same testing apparatus were used, without any modification whatever. Samples of the coke were analysed by Mr. Blount, and during the whole of the run the same method of sampling the gas was employed as in

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[1] *See* pp. 242, 243.

the anthracite tests, but the calorific value of the gas was calculated from the analyses and was not determined by a calorimeter.

TABLE XI.—TRIAL OF 40 B.H.P. SUCTION PLANT WITH COKE.

	Fuel.					Gas.						
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Heat efficiency.	
							By calculation.	By Junker calorimeter.			Lower value.	Higher value.
	Calories per kilo.	Per cent.	Per cent.	Kilos.	Calories.	Per cent. by volume.	Calories per cubic meter.		Cubic meters.	Calories.	Per cent.	Per cent.
Whole run—cold start.	6932	—	11·37	125·28	868,400	H 12·0 CH_4 0·4 CO 25·5 CO_2 5·3 O 0·65 N 56·15	1186	1189	616·88	731,700	80	**84**
Last six hours—hot start.	6932	—	11·37	94·85	657,500	H 13·2 CH_4 0·35 CO 25·3 CO_2 5·4 O 0·6 N 55·15	1212	1218	482·86	585,200	84	**89**

In the trial with coke the following quantities of water were used :—

For the vapouriser, about 25 lbs. per hour.
For the scrubber, „ 600 „ „

With these results before us, we are able to compare closely some points of interest connected with the use of coke and anthracite respectively, and we have summarised them in Table XII.

It will be seen that during the early portion of the trials, starting cold, the gas from anthracite was considerably stronger than that from coke: this was due to the fact that some hydrogen and methane were given off by the mere action of heat on the anthracite. For some little time after starting the quantity of steam generated was small, because a considerable quantity of heat

TABLE XII.—COMPARISON OF GAS MADE FROM ANTHRACITE AND FROM COKE IN 40 B.H.P. SUCTION PLANT.

	Cold start.		Hot start.	
	Anthracite.	Coke.[1]	Anthracite.	Coke.
Composition of gas (per cent. by volume)—				
Hydrogen	13·8	7·8	15·64	13·2
Methane	1·2	0·6	1·16	0·35
Carbon monoxide	21·0	26·1	20·13	25·3
Carbon dioxide	7·25	4·9	6·09	5·4
Oxygen	0·3	0·7	0·74	0·6
Nitrogen	56·45	59·9	56·24	55·15
Total combustible gases	36·0	34·5	36·93	38·85
Calorific value (higher scale)—				
Calories per cubic meter	1181	1092	1204	1212
British thermal units per cubic foot	132·7	122·8	135·3	136·2
Air required for combustion of unit volume	0·928	0·831	0·927	0·921
Yield of gas—				
Cubic meters per kilo of fuel consumed (at 0° C. and 760 mm.)	4·95	4·40	5·80	5·09
Cubic feet per ton of fuel consumed (at 0° C. and 760 mm.)	177,600	158,000	208,000	182,700
Thermal efficiency of gas plant (higher scale) . . per cent.	70·9	69·4	90·0	89·0
Heat of combustion of 1 cubic meter of an explosive mixture containing gas and air in the proportions required theoretically for combustion . . . calories	613	596	625	631
Approximate power given by an engine which will give 100 H.P. with the gas of column 3	98	95	100	101

was required to raise the temperature of the gas producer and its vapouriser up to their working value. In ordinary practice this is not much felt, because the fire remains in the producer all night, and it is seldom necessary to make a cold start. In the tests we are considering, starting cold, the thermal efficiency of the plant during the first two hours only, was 71 per cent. for anthracite, and 69 per cent. for coke. With coke the efficiency was lower, chiefly because the gas was poor in hydrogen. This will be readily understood by a glance at the following diagrams (Figs. 40, 41,

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[1] Fire lighted at 9.15 a.m.; gas right at 9.35 a.m.; test taken from 9.50 a.m. to 11.15 a.m. = 85 minutes.

and 42), in which we have shown the variations in the composition and calorific power of the gas at different hours during the trials. It is noteworthy that when the producer has reached the

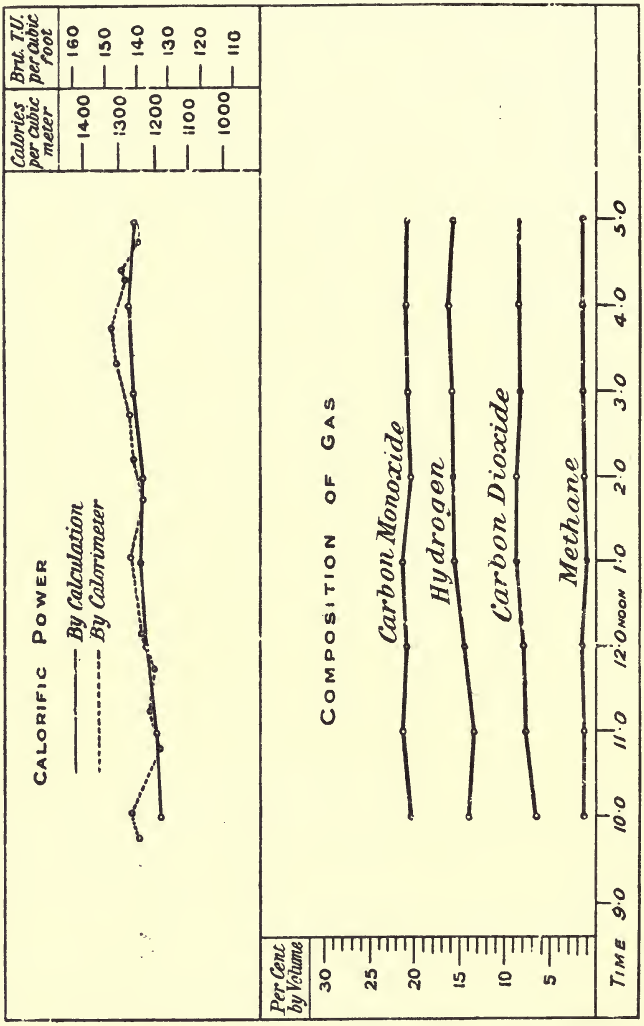

FIG. 40.—30 B.H.P. suction plant—trial with anthracite.

normal working condition the composition of the gas and its calorific power are remarkably constant.

It should, however, be understood that although the gas made at the beginning of the trials (before the producer had been thoroughly heated) was of low calorific power, it required less air for its complete combustion. A larger volume of the gas could therefore be used in an engine cylinder of given size, and the power which the engine could develop would not be reduced proportionally to the calorific power of the gas.

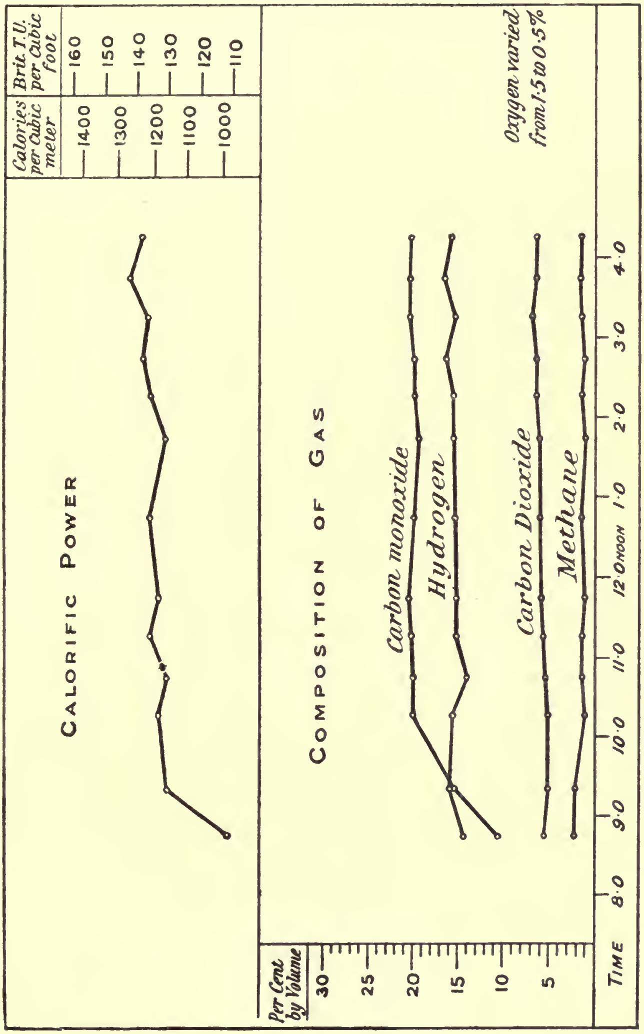

FIG. 41.—40 B.H.P. suction plant—trial with anthracite.

If, for instance, the heat energy contained in one unit volume (cubic meter or cubic foot) of a mixture of the gas mentioned in

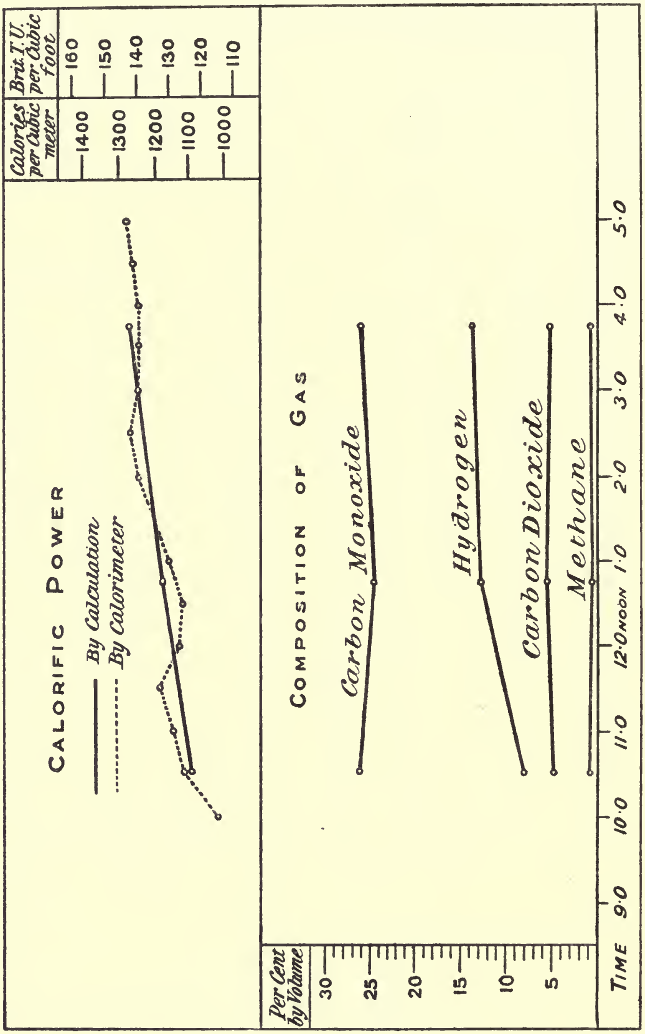

Fig. 42.—40 B.H.P. suction plant.—trial with coke.

column 3 of Table XII., with air in the proportion theoretically required for its combustion be taken as 100, the heat energy contained in one unit volume of similar mixtures of the other gases with air, would be 101, 98, and 95 respectively. Approximately, therefore, the powers which could be obtained in the same engine with these four gases would be in the proportions of 100, 101, 98, and 95.

If we compare the figures of the "hot start," *i.e.* for the last 6 hours of the run, it will be seen that the coke gas is slightly richer, and contains a higher total percentage of combustible gases. But the yield of gas per kilo of fuel consumed is considerably lower, and this is due to the poorer nature of the fuel, the coke containing 11·37 per cent. of ash, while the anthracite contained 8·76 per cent. The coke, also, had practically no volatile constituents which would enrich the gas, whereas the gas made from anthracite was considerably enriched in this way.

Before we leave this branch of the subject it will be interesting to compare the gas made in a pressure plant with that made in a suction plant. For this purpose we have taken the results obtained by Mr. Adam with a 40 B.H.P. plant, and those obtained in a careful trial of a 40 B.H.P. steam-jet pressure plant of the Dowson type. We have also given the average results of seven different pressure plants of this type of various sizes ranging from 8 to 300 H.P.[1] All the plants referred to were worked with anthracite, and the comparative results are given in Table XIII.

From this it appears that the calorific power of the pressure gas is approximately 20 per cent. higher than that of the suction gas. In the latter the percentages of hydrogen and carbon monoxide are lower, while the percentage of nitrogen is higher, and less air is required for the combustion of the suction than of the pressure gas; but after allowing for this it will be seen that (approximately) an engine which will develop 100 H.P. with the pressure gas will only give 93 H.P. with suction gas, a loss in the maximum power of the engine of 7 per cent. On the other hand, the heat efficiency of a complete pressure-gas plant with an independent boiler would necessarily be lower than that of a suction plant which produces its own steam without an independent boiler. If the steam for the pressure plant were raised by the sensible heat of the gas produced, as is sometimes done,

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[1] See *Proc. Inst. C.E.*, 1901, vol. cxliv. p. 282.

TABLE XIII.—COMPARISON OF SUCTION AND PRESSURE PLANTS.

	Suction plant, 40 B.H.P. (hot start).	Pressure plant, 40 B.H.P. (hot start).	Pressure plant. Average of seven plants (hot start).
Composition of gas (per cent. by volume)—			
Hydrogen	15·64	19·8	17·36
Methane	1·16	1·3	1·20
Carbon monoxide	20·13	23·8	25·55
Carbon dioxide	6·09	6·3	5·77
Oxygen	0·74	—	0·30
Nitrogen	56·24	48·8	49·82
Total combustible gases . .	36·93	44·9	44·11
Calorific value (higher scale)—			
Calories per cubic meter) . . .	1204	1463	1432
Brit. T.U. per cubic foot . . .	135·3	164·4	161·0
Air required for combustion of unit volume	0·927	1·162	1·122
Yield of gas—			
Cubic meters per kilo of fuel consumed in producer	5·80	5·04	5·01
Cubic feet per ton of fuel consumed in producer	208,000	181,000	180,000
Heat of combustion of one cubic meter of an explosive mixture containing gas and air in the proportions required theoretically for combustion . . . calories	625	677	675
Approximate power given by an engine which will give 100 H.P. with the gas of column 3 . .	93	100	100

we should not have to take into account the separate fuel consumption of the boiler in calculating the heat efficiency, and the figures show that the heat efficiencies of the two plants (pressure and suction) would then be nearly alike. We may therefore assume that the heat liberated by the exothermic reactions is recovered in each case to about the same extent by the endothermic reactions.

A suction plant has manifest practical advantages—it costs less, it is more simple to work, and requires much less labour and less fuel; but the gas made in it is not so strong as in the older form of pressure plant, and in some cases this advantage of the latter is important.

In June, 1906, as many as twelve different suction plants and engines of about 15 to 20 B.H.P. each were tested at Derby, on behalf of the Royal Agricultural Society of England. The chief object of these trials was to determine—as far as circumstances permitted—whether suction plants could be relied on for agricultural and estate purposes, bearing in mind that they would have to be worked by unskilled labourers. The consumption of fuel and water was also noted, and a full report of the trials was drawn up by Captain H. R. Sankey, R.E., who was one of the Judges. He thus summarises the results (p. 41):—

"From these trials it can be deduced that the following fuel and water consumptions may be expected with a good suction producer plant when working continuously at the loads specified and under the best conditions:—

ANTHRACITE.

Full load: 1·1 lb. per B.H.P.-hour, including fuel needed for starting and for banking during the night.

Half load: 1·6 lb. per B.H.P.-hour, including coal for starting.

Water: 1 gallon per B.H.P.-hour at full load, and ¾ gallon at half load.

COKE.

Full load: 1·3 lb. per B.H.P.-hour, including fuel needed for starting.

Water: 1½ gallons per B.H.P.-hour at full load."

On p. 55 he says: "It is evident from the results of the trials that many of the suction gas producer plants submitted for trial were quite satisfactory. There can be no reasonable doubt that with due care any of them would give satisfaction if employed for agricultural work as an 'estate' engine."

CHAPTER VIII

SUCTION PLANTS (CONTINUED)

When suction plants were first introduced, several makers of gas-engines feared that the increased suction in the cylinder would seriously reduce the maximum power developed by the engine, compared with that obtained with gas at pressure from a gas-holder. Some makers estimated this loss in maximum power at 20 to 25 per cent., and although this was an exaggeration the fact remains that there is a loss, and it will be well to consider what actually occurs. In the first place, we should remember that the suction in the cylinder, to draw in the required volume of gas and air, is distinct from the additional suction required to draw air into the producer and gas through the plant and mains. In the next place, we should remember that when gas at pressure is used it passes through an elastic gas-bag, which to a certain extent keeps up a gas pressure during the suction stroke, and that when a suction plant is used the gas is never above the atmospheric pressure. In the one case we have a head of gas at pressure to draw from; in the other no head of gas, and the pressure in the gas main falls below atmospheric as soon as the engine begins to draw in its charge.

There are various systems of governing a gas engine. In this country the usual system is the "hit-and-miss" (*tout ou rien*), in which the gas only is governed, the quality of the mixture of gas and air admitted being constant, while the charge is admitted at intervals to suit the varying load. On the continent the almost invariable practice is to admit gas at every cycle, but to govern the quantity of the mixture of gas and air admitted, the quality being constant. There is good in both these systems, the chief advantage of the throttling system being that there is a more even turning movement. It would, however, be beyond the scope of this work to discuss this interesting question in detail, but especially in connection with suction plants we should consider the loss of power caused by the suction of air when the gas-valve is closed during the governing stroke in engines using the hit-and-miss system. This does not affect the maximum power of the engine, but it is a practical question of importance because it does affect every governing stroke, and in average work an engine is usually working at about one-third less than its maximum output. This does not occur in the throttle system where there is no air drawn in between the explosions. The losses of power so far referred to are the direct losses due to fluid friction; they occur with both pressure and suction working, but may be greater in the latter than in the former case: they are considered in detail later in this chapter. The principal loss of power arises in an indirect manner, and as this is the most important we discuss it first.

For the purpose of comparison we will assume that the gas from a suction plant has the same calorific power as the gas from a pressure plant, also that the gas and air supplies on the engine are regulated to give the best explosive mixture obtainable. The charge then drawn into the cylinder will have the same composition, and the difference to be considered will be the *amount* of the charge in each case. Usually the admission valves close a little after the piston has completed its outstroke, but they do not remain open long enough for any portion of the charge to be expelled at the beginning of the compression stroke. Therefore in each case the same *volume* of charge is drawn in, viz. that equal to the volume swept out by the piston. In both cases the pressure of the charge is below that of the atmosphere while the admission valve is open; but in the case of gas from a suction plant this pressure is lower than when the gas is supplied at pressure, and therefore the *quantity* or weight of the charge is less. We shall not be far wrong in assuming that in a modern gas-engine the pressure in the cylinder falls to $1\frac{1}{2}$ lbs. per square inch below atmospheric pressure during the suction stroke, when gas at pressure and air are being drawn in.[1] But to compare the quantities of gas drawn in we should know the pressures at the *end* of the suction stroke when the cylinder is full. According to Mr. Clerk,[2] when pressure gas

[1] *See* p. 144.

[2] "The Gas Engine," p. 308 and Fig. 125.

is used and when the valves are properly set the pressure at the end of the suction stroke rises to that of the atmosphere. In some early experiments with a 40 B.H.P. engine working with a suction plant the pressure in the cylinder was about 1½ lbs. below atmospheric at the end of the suction stroke, as shown in Fig. 43. This pressure was, therefore, 13·2 lbs. per square inch, compared with 14·7 lbs. per square inch for pressure gas. The weights or quantities of explosive mixture would be in the same ratio, and the maximum power of the engine—confining our attention to this cause only—was $\frac{13{\cdot}2}{14{\cdot}7}$, or 90 per cent. of its maximum power when working with gas at pressure. The pressure in the cylinder at the end of the suction stroke should not be more than 0·5 lb. per square inch below atmospheric; the maximum power would then be $\frac{14{\cdot}2}{14{\cdot}7} = 96{\cdot}6$ per cent. of the maximum power of the same engine working with gas at pressure.

When an engine is working with pressure gas from a gas-bag and gasholder it is probable that the pressure on the supply side of the gas-cock on the engine does not fall to more than 3 ins. of water below atmospheric during the suction stroke; but we have seen that the pressure in the cylinder is 1½ lbs., or about 42 ins. of water, below that of the atmosphere. This shows that however plentiful the supply of gas may be the piston moves forward so quickly that there must be a considerable wire drawing. In the case of working with suction gas, as in Fig. 43, the suction on the supply side of the gas-cock was 11½ ins., and it might be expected that the pressure in the cylinder during the suction stroke would be reduced much more than when pressure gas was used. Actually the pressure on the diagram shown is not more than 2 lbs. below the atmospheric. At the end of the suction stroke, which for the moment is the important point to consider, the piston moves comparatively slowly as the crank approaches the horizontal position, and with pressure gas (having a pressure equal to a few inches of water) the gas continues to flow into the cylinder, and the pressure in the latter rises, practically to atmospheric, as stated above. With suction gas, although Fig. 43 shows a slight rise of pressure (from 2 lbs. to 1½ lbs.

below atmospheric), at the end of the suction stroke when the piston is moving more slowly, the pressure does not rise to the same extent as with pressure gas. The reason for this is that there is only the reduced pressure in the cylinder to draw the gas through the producer, scrubber, etc., and gas valve, instead of there being gas at pressure on the inlet of the gas cock, as in the other case. It should also be noted that the higher the speed of the engine the greater will be the loss of power from this cause; and that the gas and air valves should therefore be held open as long as possible after the out centre has been reached, without risking the expulsion of gas at the beginning of the compression stroke.

With these facts in view it is clearly important to reduce the resistances in the gas plant to a minimum; the connecting pipes between the engine and plant should be fully large, and with as few bends as possible; and it is also desirable to have an enlarged pipe or gas-box close to the engine so that there may be a reserve of gas to draw from. In this way the fall of pressure in the gas main is reduced; and what is now usually termed an expansion box takes the place of the gas-bag used for pressure gas. This expansion box can also be used to catch any condensed moisture from the gas, if the main leading to it has a fall in that direction.

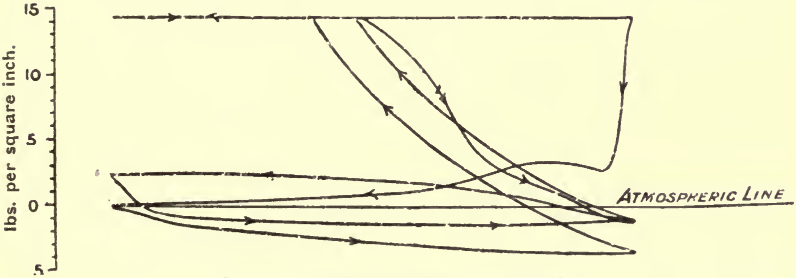

Fig. 43.—Suction diagram (light spring).

To reduce the suction it is usual to place the engine tolerably near the gas plant; but provided the main is direct and of ample size it is quite satisfactory if the engine is 50 ft. from the plant. With a well-designed plant the suction near the engine will then be from 8 to 10 ins. of water or even less. If the distance is greater than 50 ft. special care should be taken to avoid friction in the pipe. We have had to deal with a case where the engine was about 150 ft. from the plant, and yet the gas suction in the expansion-box near the engine was only 11 ins. of water. Where two or more engines are to be served by one suction plant, or where there are two engines and two plants and the sets are to be interchangeable so that either plant can serve either engine, a special arrangement of piping and shut-off valves should be adopted. The chief consideration should be to avoid complications and excessive friction; the number of valves and bends should be minimised. In some cases it is best to have a suction fan between the engines and gas plant, so as to draw gas from the latter and deliver it at pressure to the engines.

To complete our comparison of working with pressure or suction gas we will now revert to the engine itself and refer briefly to the subject of fluid friction. When an engine works with a suction plant there is obviously a direct loss due to the action of the piston as a suction pump, and it is often supposed that this is the chief loss when working with suction gas. The engine is its own pump, and this necessarily involves loss of power; but actually this loss is a small one, and is not nearly as great as the other losses which have to be taken account of. Taking Mr. Clerk's statement[1] that when pressure gas is used the pressure in the cylinder during the suction stroke falls to $1\frac{1}{2}$ lbs. below the atmospheric, we can compare this with Fig. 43, which shows that with suction gas the pressure in the cylinder falls to 2 lbs. below atmospheric. In the latter case, the work done by the engine as a pump, over and above the similar work which it would do when supplied with gas from a gasholder and gas-bag, is equal to 0·5 lb. × piston area × stroke × number of power strokes. This loss is greatest when the engine is working with a full load, and taking the case of an engine developing a maximum of about 40 B.H.P. (with producer gas), the cylinder may be taken as 13 ins. diameter, the stroke 20 ins., and the number of revolutions per minute 170. The loss of power due to this extra half-pound suction will then be $0{\cdot}5 \times 132{\cdot}7 \times \frac{20}{12} \times 85 \times \frac{1}{33000} =$ about 0·3 H.P. From this

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[1] *Journal of Soc. Arts*, 1905, vol. liii.

cause alone the maximum indicated horse-power will therefore be reduced by only 0·3, compared with that obtained with gas at pressure.

Another point referred to above is the indirect loss due to the fact that the air inlet to the engine must be smaller for suction than for pressure gas, so that with hit-and-miss governing the negative work of the idle stroke is increased. When the engine is not fully loaded and the governor allows the gas valve to remain shut, air alone is drawn into the cylinder on the suction stroke; and when this occurs the pressure in the cylinder behind the piston is always lower than when both gas and air are admitted. The reason of this is that on the governing stroke the whole contents of the cylinder are drawn through one opening (the air inlet), instead of through two openings (the gas and air inlets). This occurs with suction or pressure gas, but when suction gas is used the suction in the cylinder is greater, and consequently the air inlet must be smaller, if the proportions of gas and air drawn in for the useful cycles are to be the same in both cases. It follows, therefore, that the loss of power by fluid friction on the idle cycles is greater when working with suction than with pressure gas.

In Fig. 43 the lowest line of all represents the suction stroke when the gas valve remains closed; this shows a pressure of $5\frac{1}{2}$ lbs. per square inch below atmospheric during more than half the stroke, and the average for the whole stroke is about 4 lbs. per square inch. If we assume that with pressure gas the average would be 3 lbs. per square inch, with suction gas it would be one pound more, and on this basis the extra loss of power would be about half a horse-power for the 40 H.P. engine when the engine is running light. We believe that rather better results have been obtained, but we wish to emphasise rather than to minimise the differences we are discussing, so that attention may be drawn to certain directions in which improvements may be sought. With engines governed by throttling the mixture of gas and air, there is no difference in the fluid friction losses with pressure and suction gas when working below full load.

Hitherto we have dealt more particularly with engines and suction plants working under full load, and we should now consider what occurs with light and variable loads. We have seen that in a suction plant the *quantity* of gas produced is regulated exactly by the action of the engine, as there is a draught of air and steam through the producer every time that gas is admitted to the engine. If the latter is of the Otto type, when there is a full load the gas valve opens at every fourth stroke; but when there is a light load the valve is opened less frequently, and consequently there are longer intervals between the intakes of air which are drawn through the producer. It is therefore important to consider how this varying quantity of air affects the condition of the fire and the composition of the gas, especially in view of the fact that in many installations the load may vary within wide limits.

Some gas-producers are better than others, but it is safe to say that none make gas of equal calorific power at all rates of production. They may make gas good enough to drive engines with varying loads, but as our object should be to improve in all directions possible it is worth while to examine this branch of the subject more closely. Speaking generally, the best gas will be produced when the producer is worked uniformly at its maximum, or nearly its maximum capacity; at any rate of production considerably less than the maximum the calorific power of the gas will be lower. To illustrate this, we will take the case of a 40 B.H.P. engine working with a full load, and with no load at all. We made this test with ordinary gas-coke in the producer; and although somewhat better results can now be obtained, those we give will serve as an illustration of comparison. The full-load test was made when the fire was in good working order, and the no-load test began by throwing off the load and the belt, while the engine continued to run. The latter test lasted three-quarters of an hour. The following table gives analyses which represent the average composition of the gas in each test:—

TABLE XIV.—COMPOSITION OF GAS WITH FULL LOAD AND NO LOAD ON ENGINE.

	Per cent. by volume.	
	At full load.	At no load.
Carbon monoxide	27·65	22·4
Hydrogen	9·85	7·0
Carbon dioxide	3·8	4·9
Oxygen	0·3	0·5
Nitrogen, etc.	58·4	65·2
	100·0	100·0
	Calorific power.	
Calories per cubic meter	1147	899
Brit. T.U. per cubic foot	128·9	101·0

A further useful illustration is afforded by the trials made at Derby, referred to on p. 138. To test the working of the different suction plants at widely different loads they were run for two hours with no load immediately after starting up in cold producers, then for one hour at full load, another hour with no load, and for further successive periods of one hour each at one-quarter, one-half, and full loads. We made use of this opportunity to collect samples and analyse the gas made in a 20 B.H.P. Dowson plant under these varying conditions, and we give the results in the following table:—

TABLE XIV*a*.—COMPOSITION (PER CENT. BY VOLUME) OF GAS MADE WITH ANTHRACITE UNDER DIFFERENT LOADS IN 20 B.H.P. DOWSON PRODUCER AT DERBY.

	Conditions.	CO.	H_2.	CH_4.	CO_2.	O_2.	N_2.	Calorific power.	
								Brit. T.U. per cubic foot.	Calories per cubic meter.
1	First hour, no load	10·2	11·05	2·75	11·2	0·1	64·7	102·7	913·9
2	Second hour, no load	12·45	12·15	2·0	10·1	—	63·3	105·8	941·5
3	Third hour, full load	22·25	15·9	1·95	5·25	0·1	54·65	152·3	1355·3
4	Fourth hour, no load	18·3	13·6	1·2	9·05	0·3	53·55	122·8	1092·7
5	Fifth hour, ¼ load	20·0	11·8	0·75	8·35	0·1	59·05	117·5	1045·6
6	Sixth hour, ½ load	20·9	14·0	0·7	7·7	—	56·7	127·7	1136·4
7	Seventh hour, full load	21·5	14·5	1·2	7·6	—	55·2	136·8	1217·3

It will be seen that the difference in the composition of the gas is that it contains smaller percentages of carbon monoxide and hydrogen, and larger percentages of carbon dioxide and nitrogen during the no-load periods, and it is noteworthy that while the gas made with no load on the engine, immediately after starting in a cold producer, has a low calorific power and does not materially improve while the producer continues to work without load, yet after the producer has worked for a time at full load, has become thoroughly heated up, and contains a good depth of bright fire, it gives gas of considerably higher calorific power than before, when the load is again removed. The explanation of this is mainly a question of temperature. At full-load the intermittent draughts of air through the fire follow one another in quick succession, and the fuel is maintained at a high temperature; when there is no load there are comparatively long intervals between the in-takes of gas, so that in the producer there are short sharp suctions of air with intervals between them during which the temperature of the hot fuel falls. After the producer has been working for a little time at full load, the depth of bright fire is sufficient to make good gas during each of these periods of suction, and the temperature does not at once fall off, so that the producer continues to make fairly good gas for a considerable time after the load has been removed.

If the producer were worked by the continuous suction of a fan instead of by the intermittent suction of an engine the effect during the no-load period would not be quite the same. With a fan there would be a steady draught of the volume of air required, and there would be a shallow zone of fire near the grate, which would be maintained at a sufficiently high temperature to make good gas; and gas of good quality would be produced as long as this hot zone was sufficiently deep in relation to the size of the fuel. If the air for the producer were drawn in by an engine without load a greater depth of fuel would be heated by reason of the more rapid draught of air through the fire; but a good deal of heat would be dissipated before the next suction. This points to the importance of maintaining the temperature of the fire as high as possible when the gas plant is worked at a reduced load by the suction of an engine; and a step in this direction is to reduce the quantity of steam proportionally to the volume of air drawn in. This was done approximately during the no-load test above referred to (Table XIV.), but frequently no attempt is made to vary the proportion of steam. If the production of steam is continuous while the in-draught of air is intermittent it follows that after each interval there must be an excess of steam mixed with the air, unless some way of regulating the production or admission of the steam is adopted. If there is too much steam during the light loads this of itself lowers the temperature of the fire and adds to the trouble caused by the small amount of air drawn in. If the air is heated before it reaches the fire, this also will assist to maintain the temperature required.

It is well known that after an engine has been working under a light load for some time with a suction plant there is a risk of stoppage if the full load is put on suddenly. Moreover, when this occurs it is not uncommon to attribute the stoppage to an insufficient supply of gas. This is incorrect, as the volume of gas necessarily varies directly in proportion to the load on the engine; it is the *quality* of the gas which is wrong, and the explanation of this fact is not far to seek. During the light load the temperature of the fire has fallen, and for a few moments after the full load has been put on there is too little hot fire and what there is is not hot enough to effect the necessary chemical reactions. The chief defects are that there is too little hydrogen, and that too little of the carbon dioxide is reduced to the monoxide. The remedy is to put on the full load more gradually, so that the engine may be kept running at full speed in spite of the weakness of the gas; the fire in the producer will then recover rapidly, and there will soon be a full supply of gas of good quality. These changes are clearly shown in the series of indicator diagrams shown in Figs. 44–50, the adjustments of the gas and air supplies to the engine being unaltered throughout the tests so that the variations in the mean pressures were due to variations only in the quality of the gas. The engine was worked with a light load for seventy minutes, and then the full load was suddenly applied, with the following results:—

Fig.	Time.	Mean pressure of indicator diagram—pounds per square inch.
—	2.50 p.m. load off	
44	3.5 ,, ,,	76
45	3.15 ,, ,,	74
46	3.25 ,, ,,	74
47	3.45 ,, ,,	73·5
48	4.0 ,, full load on	decreasing
49		increasing
50		81·5

The diagrams shown in Figs. 48, 49 and 50 were taken in succession, immediately after putting on the full load: while

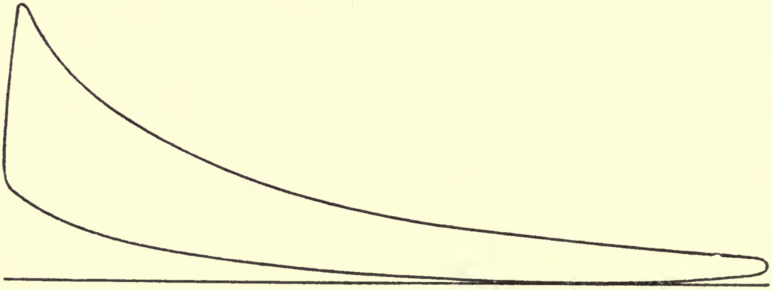

Fig. 44.

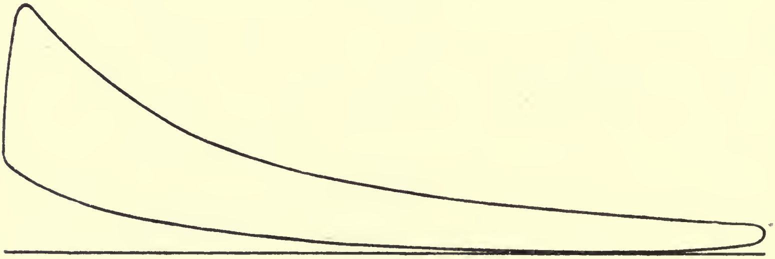

Fig. 45.

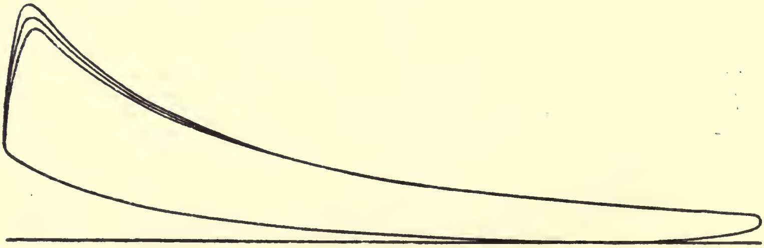

Fig. 46.

Fig. 48 was being taken the explosions became weaker and weaker; while Fig. 49 was being taken they became stronger and stronger;

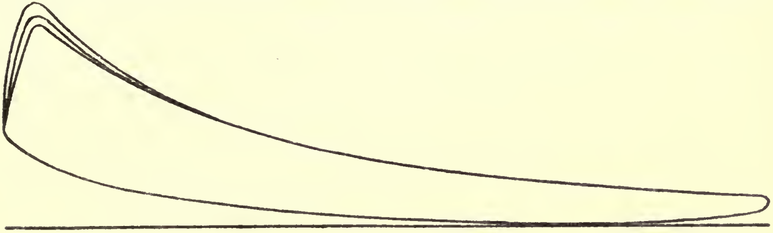

FIG. 47.

FIG. 48.

FIG. 49.

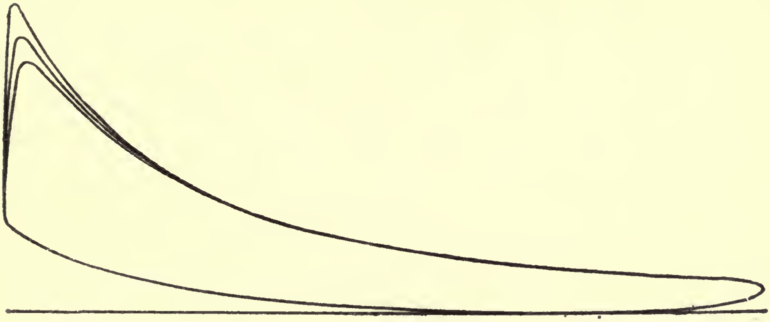

FIG. 50.

and when Fig. 50 was taken the fire in the producer had regained its normal condition, and the explosions were regular and good.

The explanation seems clear. While there was no load on the engine the temperature of the fire was reduced, and the heat required to make the gas existed only in the lower part of the producer near the grate. When the brake was suddenly applied to the engine it at once began to draw in more gas; and consequently more steam and air were drawn into the producer fire. But the fire was not hot enough, nor was there a sufficient depth of hot fuel to complete the reactions. Not all the steam was decomposed, and too little of the carbon dioxide was reduced. The effect would be similar to that of blowing up a rather dull and shallow fire with air saturated with moisture. Until the increased draught had had time to produce a good depth of bright fire there would necessarily be a deterioration in the quality of the gas. As bearing on this question we may mention another test we made. On this occasion gas was made with anthracite and the engine was run without a load. The brake was then suddenly applied and in a short time the engine stopped. Immediately after it stopped, a sample of gas was drawn from the main near the engine, and on analysis it showed the following composition :—

Carbon monoxide	16·2	per cent.	by volume.
Hydrogen	11·9	,,	,,
Methane	0·25	,,	,,
Carbon dioxide	9·4	,,	,,
Oxygen	0·9	,,	,,
Nitrogen	61·35	,,	,,
	100·00		

The calorific value was only 884 calories per cubic meter, or 99·4 Brit. T.U. per cubic foot.

By way of illustration, we have thought it best to take the extreme case of an engine running for some time without a load, the full load being then suddenly applied. This would seldom occur in ordinary practice, and the variations would not be so noticeable under the ordinary variations of load; but the principle holds good, and we cannot but emphasise the importance of maintaining, as far as possible, a sufficient depth of fuel at a sufficiently high temperature for whatever variation of load may be put on the engine. Assuming that the producer is properly designed, there should be no difficulty in fulfilling these conditions under a full load or any intermediate load down to half load or less.

During the Derby trials with anthracite we took numerous samples of the gas made in the 20 B.H.P. Dowson plant, and the following represent the average analyses (per cent. by volume) for full and half loads:—

	Full load.	Half load.
Carbon monoxide	21·95	18·9
Hydrogen	13·85	14·05
Methane	1·55	1·60
Carbon dioxide	7·2	8·05
Oxygen	0·1	0·05
Nitrogen, etc.	55·35	57·35
	100·0	100·0
	Calorific power.	
Calories per cubic meter	1243·5	1161·5
Brit. T.U. per cubic foot	139·7	130·5

It will be seen that at half load there is less CO and more CO_2 and N, owing to the lower temperature in the producer. Consequently the gas is weaker, but it is satisfactory to note that the difference is not great between full load and half load.

There are many engines and suction plants which are working well with smaller loads, but if the gas were analysed it would probably be found to be not of the same quality as it is with the full load, for the reasons already stated. When all or a considerable part of the load is thrown off after working with a full load the quality of the gas will at first be good, because at first there will be more steam than before in proportion to the air drawn in, and the fire will be deep enough and hot enough to decompose it; but this effect will last for a short time only. There is no difficulty in working a suction plant with a steady load which is only a small fraction of its maximum; the difficulty arises only when the load is increased suddenly. We are aware that several devices have been tried to get over the difficulty; we need not discuss them here as we are merely dealing with the principles involved, and doubtless sooner or later means will be found for doing all that is necessary. The wonder is that so much has already been accomplished in the short time which has elapsed since M. Bénier's first attempt in 1891.

An important feature with a suction plant is the small amount of labour it requires, and the readiness with which gas can be made. With plants up to about 100 B.H.P., the engine can be started in 15 to 20 minutes after lighting the fire in the producer; and not much longer time is needed for larger plants. The producer is then left full of fuel, and the attendant need put on more only at long intervals. In the Report on the Derby trials, Captain Sankey says that, taking a broad view of the results, "a suction gas plant can be started and the full load put on in about 25 minutes from the time of laying the fire, and in 20 minutes from starting the fan if the fire is banked." It has been a matter of surprise that the engine can be started so soon after lighting the fire, and it has been noticed that if the engine is not started promptly the gas is no better when the fire is blown up for a much longer time. The probable explanation is that the wood with which the fire is lighted and the mass of new fuel in the producer soon yield rich hydrocarbon gases; but after a certain time these are exhausted, and then producer gas of the ordinary kind is made.

After the engine has been started, if the adjustments of air and gas are right, it should continue to work with a constant or varying load, and as long as it works it should regulate automatically the quantity of steam and air drawn into the fire. In this way it will govern the rate of producing the gas to suit its own varying consumption.

CHAPTER IX

GAS FROM BITUMINOUS COAL FOR ENGINE WORK

When Mr. Dowson introduced his gas plant for engine work (1879),[1] the largest gas-engine then made developed under 20 B.H.P., and for various reasons several years elapsed before engines of 50 and 100 B.H.P. came into use. As the fuel consumption was not much over 450 grams (1 lb.) per B.H.P.-hour, the total amount of fuel required was comparatively small, and the mere cost of the fuel per ton was less important than the certainty of having a clean gas free from tar. He therefore worked with anthracite or coke, as these fuels gave much less trouble than bituminous coal, and it is still the general practice to use these fuels, not only for small powers, but also for large powers where bituminous coal costs nearly as much as small anthracite or small gas-coke. In cases, however, where an appreciable saving can be effected by using bituminous coal it is certainly better to use it, provided that the gas can be made clean and suitable. The general aspect of the question has, in fact, altered considerably during the last few years. Many gas-engines of 1500 to 2000 B.H.P. each are now working satisfactorily, and there is no doubt that gas power has a recognised position, even for large powers. It is generally believed that its extension in the near future will be very considerable. It is true that at the present time most of the large gas-engines are working with blast furnace gas; but some of them are working with producer gas, and it is all-important that there should be gas plants which can convert the cheapest kinds of fuel into gas suitable for large gas-engines. Moreover, for large powers the use of bituminous coal has an important bearing on the competition of gas power with steam power, because in places where steam coal can be bought at a much

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[1] *See* Chapter VI., p. 98.

lower price than anthracite or coke, the saving in weight by using either of the latter in a gas plant might be more than counterbalanced by the lower price of the steam coal used for firing boilers.

The problem is a difficult one, as the gas must be free from tar, or it will foul and clog the valves and gas passages of the engine. There is nothing new in making gas from bituminous coal; this has been done from the first for furnace work—in fact, it is an advantage to have hydrocarbon vapours mixed with the gas when it enters the furnace, because they add appreciably to the heat of combustion. But for engine work there must be no condensable hydrocarbons and no soot with the gas.

Dr. Ludwig Mond was the first to attack this difficult question on a full working scale; but it is interesting to note that what he first attempted was the production of gas for furnaces and the recovery of ammonium sulphate as a by-product: the working of engines with this gas followed afterwards. Nevertheless, we are indebted to him for the introduction of an ingenious and interesting gas plant which has many excellent features. The Mond producer is shown in Fig. 51, and it will be seen that it has a water bottom for drawing out the ashes and clinker; there are also sloping firebars at the base of the producer suitably arranged for poking the fire. The body of the producer is lined internally with firebricks, and outside the body there is an outer casing. The producer is worked with a blast of air from a blower, mixed with a large excess of steam—about 2½ kilos of the latter for each kilo of coal converted into gas; the steam and air pass through the annular space between the body and the outer casing, and thence through the firebars. The chief object of this large excess of steam is to keep down the temperature of the fire, and by doing this a twofold effect is produced. In the first place, it prevents the destruction of the ammonia gas (NH_3); in the next place, it checks the formation of clinker, and thus facilitates the continuous working of the producer. It is said that only half a kilo of steam is decomposed for each kilo of fuel gasified, so that when the gas leaves the producer it is accompanied by a large amount of steam. To reduce the loss on this account, as well as to assist the process, the hot gas and steam are made to give up some of their heat to the air which is driven into the producer. This is effected by means of a tubular regenerator, the hot gas from the producer passing in one direction through an inner series of pipes, while the hot air and steam from an air-heating tower pass in the opposite direction through an annular enclosure round the gas main. The steam and air are further heated by passing round the producer itself, as described above.

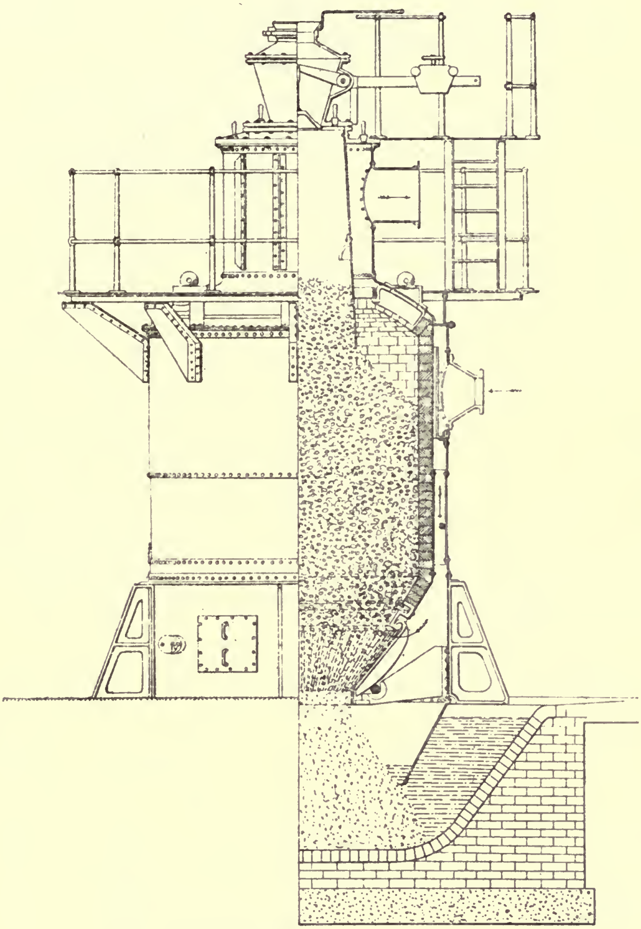

Fig. 51.—Mond gas producer.

After leaving the regenerator, the gas and undecomposed steam pass through a washer and are cooled down to about 90° C. (194° Fahr.); here the gas takes up a further quantity of vapour by evaporation. The gas then goes upwards through a lead-lined tower packed with tiles, and meets a current of acid liquor (circulated by pumps) containing sulphate of ammonia with about 4 per cent. excess of free sulphuric acid. Combination of the ammonia of the gas with the free acid takes place, so that more ammonium sulphate is formed, and when the gas has been freed from ammonia it is passed through a cooling tower, in which it meets cold water; after this it is ready for use. There is a third tower (called the air-heating tower) in which the hot water from the cooling tower descends, meeting the supply of cold air which is on its way to the regenerator and so heating it and saturating it with water vapour. The regenerative system has been skilfully applied, and the general outcome of the process is that from 70 to 90 lbs. of ammonium sulphate are recovered per ton of coal gasified. The amount of sulphate produced and the composition of the gas depend a good deal on the composition of the coal, especially as to the percentage of nitrogen it contains. In a recent paper by Mr. W. L. Case,[1] the following are given as the averages of several analyses of the gas produced in the Mond plant, with and without the recovery system:—

TABLE XV.—AVERAGE COMPOSITION OF GAS MADE IN MOND PLANT.

		With recovery of ammonia.	Without recovery of ammonia.
Hydrogen	Per cent. by vol.	24·3	27·5
Methane	,, ,,	2·0	2·0
Carbon monoxide	,, ,,	13·8	11·0
Carbon dioxide	,, ,,	13·9	16·5
Nitrogen, etc.	,, ,,	46·0	43·0
		100·0	100·0
Total combustible gases	,, ,,	40·1	40·5
Calories per cubic meter at 0° C. and 760 mm.		1361·0	1375·0
Brit. T.U. per cubic foot	,, ,,	153·0	154·6

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[1] *Journal Soc. Chemical Industry*, 1905, vol. xxiv. p. 596.

Mr. Case further states that the coal used in both cases was slack, giving the following average analysis :—

Moisture at 100° C.	8·6	per cent.
Volatile matter (excluding carbon)	18·29	„
Total carbon	62·69	„
Ash	10·42	„

For further details of tests made with this interesting plant, we cannot do better than refer to papers read by the Mond Company's engineer, Mr. H. A. Humphrey.[1]

One of the disadvantages of using bituminous coal with a large excess of steam is that a complicated and costly regenerative plant is necessary to secure even an efficiency of 80 per cent.; another is that the high percentage of hydrogen adds to the risk of pre-ignitions if the compression in the engine is raised to the point required for its highest efficiency. The gas has, however, been proved to be suitable for engine work, and already the South Staffordshire Mond Gas Company have obtained the necessary Parliamentary powers, and have carried out a large undertaking for the distribution of producer gas in South Staffordshire.

Fig. 52 is reproduced from a photograph, and gives a general view of the plant in question. The present plant consists of 8 producers, each capable of gasifying about 20 tons of coal per day, together with duplicate ammonia recovery, gas washing and cooling apparatus; also the necessary boilers, machinery, pumps and compressors. The plant has been laid out so that it can eventually be extended to 32 producers, capable of gasifying over 600 tons of coal per day, and Parliamentary powers have been obtained for distributing the gas over an area of 120 square miles. The scheme is a bold one, not only from a financial but also from an engineering point of view, and the result is awaited with keen interest. The trunk mains which leave the central station are 914 mm. (3 ft.) diameter, and the distributing mains are of various sizes; all are made of steel, and are coated first with asphalt, then with canvas, and finally with a second coat of asphalt, the thickness of the coating being about 6 mm. altogether. Owing to the high specific gravity of the gas (0·8 if air = 1), the long distances it has to

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[1] *Proc. Inst. C.E.*, 1897, vol. cxxix. p. 190; *Proc. Inst. M.E.*, 1901, p. 41.

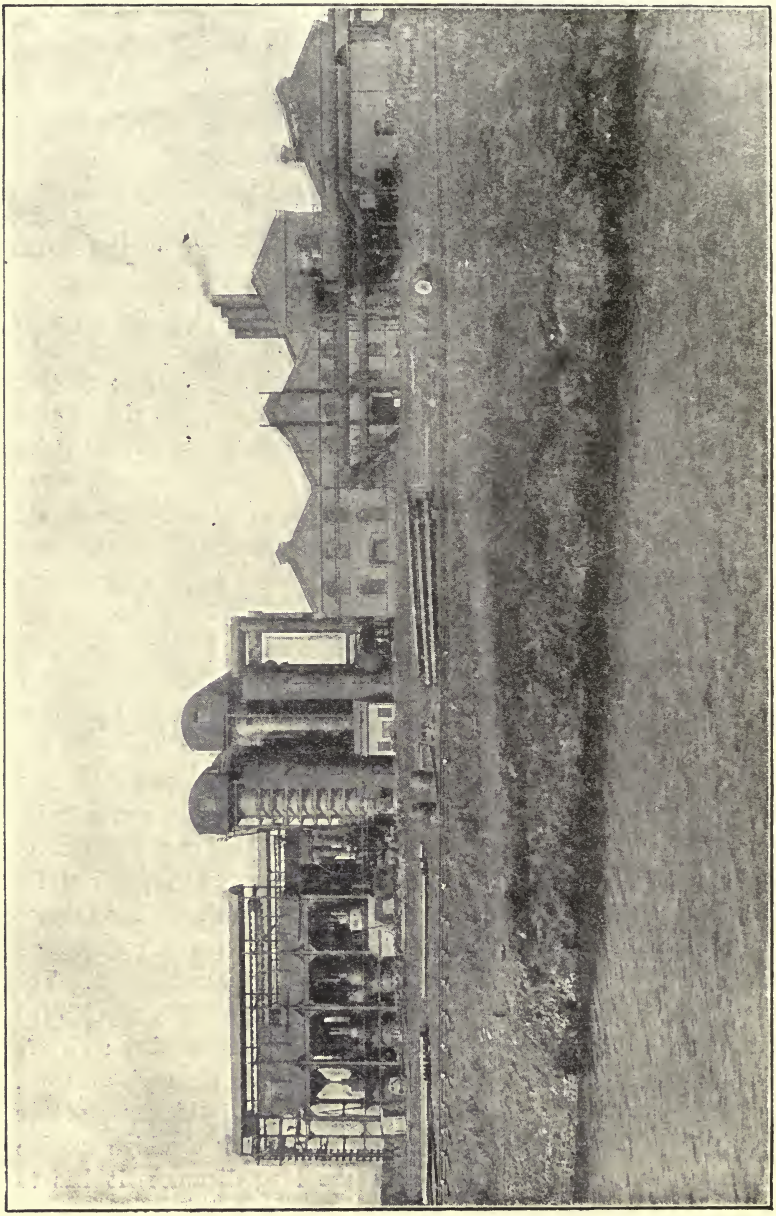

Fig. 52.—Gas plant of the South Staffordshire Mond Gas Company.

be conveyed, and the necessity of keeping the sizes of the mains within practical limits, the gas is forced through the mains at a pressure of about 0·7 kilo per square centimeter, or about 10 lbs. per square inch. For this purpose gas compressors are used, and they are shown in Fig. 53. Each set has two steam cylinders 457 mm. (18 in.) diameter, working with steam at a pressure of 8·4 kilos per square centimeter, or 120 lbs. per square inch; and two gas-compressing cylinders 1016 mm. (40 in.) diameter, with a stroke of 1067 mm. (42 in.). Each compressor is capable of delivering 266 c.m. or 9400 cub. ft. of gas per minute, at a pressure of 0·7 kilo per square centimeter, or 10 lbs. per square inch, and requires about 430 B.H.P. The exhaust steam from the compressors is used in the gas producer. A reducing valve is supplied to each consumer, so that he can regulate the pressure at which he takes the gas into his works or premises; and to measure the gas consumed he has a small rotary meter (the principle of which somewhat resembles that of an anemometer for measuring air), which is said to be fairly accurate. Special joints have been adopted for the mains, because it is not only important to prevent waste of gas, but to prevent leaks—on account of the carbon monoxide in the gas.

A portion of the plant has been working for some months; and there are some consumers, but not enough at present to test the full working cost of the system, or to justify figures being put forward as to the general outcome of the undertaking. As an engineering problem, it has been shown that producer gas suitable for driving gas-engines and for heating furnaces, etc., can be made from bituminous coal on a large scale of working, and that it can be distributed through miles of piping; but we have yet to know whether it can compete successfully with producer gas made by the consumer on his own premises.

For furnace work the valuable heat-giving hydrocarbon vapours have been removed in the process of cooling and washing; the sensible heat of the gas when it leaves the producer is also lost, so far as the heating of furnaces is concerned; and the cost of distribution and the interest on a large capital outlay have also to be paid for. For driving gas-engines, it will be difficult for the distributed gas to compete successfully with suction plants

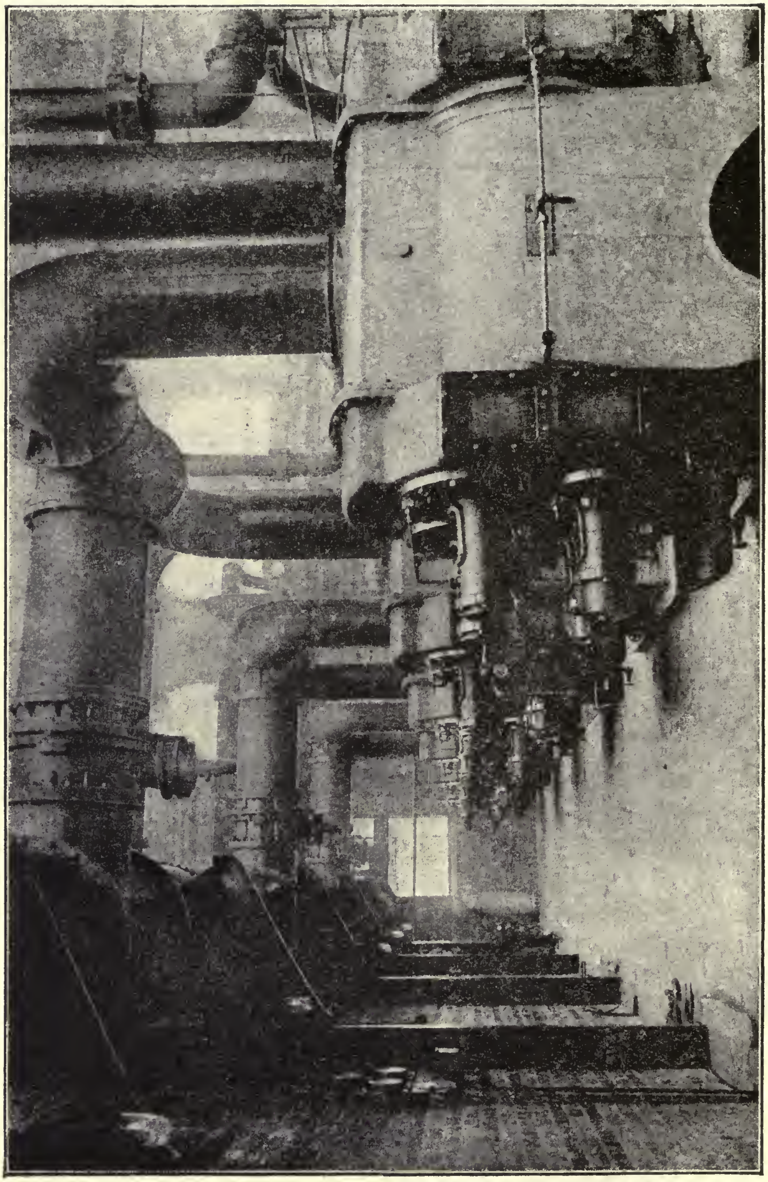

Fig. 53.—Gas compressors for forcing gas through mains.

working with small gas-coke, seeing that their first cost is moderate and that they need so little attention. Time alone can decide these interesting questions, and if it can be proved to be commercially successful to convey gas of low calorific power long distances, and to distribute it over wide areas, the idea of converting the coal into gas at the pits and conveying the gas in pipes to towns may at last be realised.

The ammonia recovery plant is somewhat complicated and is certainly costly, and we believe it is not recommended for smaller powers than 4000 to 5000 B.H.P.; moreover, it is desirable that the plant should work night and day without a stop. It is, therefore, beyond the reach of the large number of manufacturers and others who require about 500 to 800 B.H.P., and for cases of this kind the Mond plant is constructed without apparatus for the recovery of ammonia. Its principle of working is then much like that of the Wilson and other plants which make gas from bituminous coal. A recent example of a Mond plant of this type is shown in Figs. 54 and 55, the former being taken from a photograph, and the latter being a plan to explain the various parts of which the plant consists. The plant is to serve a maximum of 500 B.H.P., and is used by the Co-operative Wholesale Society at their works at Irlam. It will be seen that there are a gas-producer, boiler, steam-engine and blower, superheater, washer, governor, two centrifugal tar extractors, and a sawdust scrubber. The plant is far more complicated and more costly than a steam-jet pressure plant working with coke, and it requires more labour; it is also much less simple than a suction-plant; but it is able to work with local bituminous coal. We have not received particulars of the cost of working and cannot therefore make an exact comparison of the two systems.

Messrs. Crossley make a bituminous plant in which they use a high-speed centrifugal tar-extractor which is said to be efficient within certain limits of temperature. In the Wilson plant, made by the Horsehay Company, the tar is removed chiefly by cooling, care being taken not to let the gas come in contact with water until it has been cooled. Other makers seek to remove the tar from the gas in various ways after it has left the producer; but in all plants of this type the working is somewhat complicated, the initial outlay is considerable, and the ground space required is large.

Several methods have been proposed for converting the tarry vapours into fixed gases by passing them through a zone of incandescent fuel in the producer itself. In some cases (*e.g.* in the Mason producer) tarry vapours are drawn off from the raw fuel in the upper part of the producer as the fuel becomes gradually heated by the fire below, and are made to enter the producer again

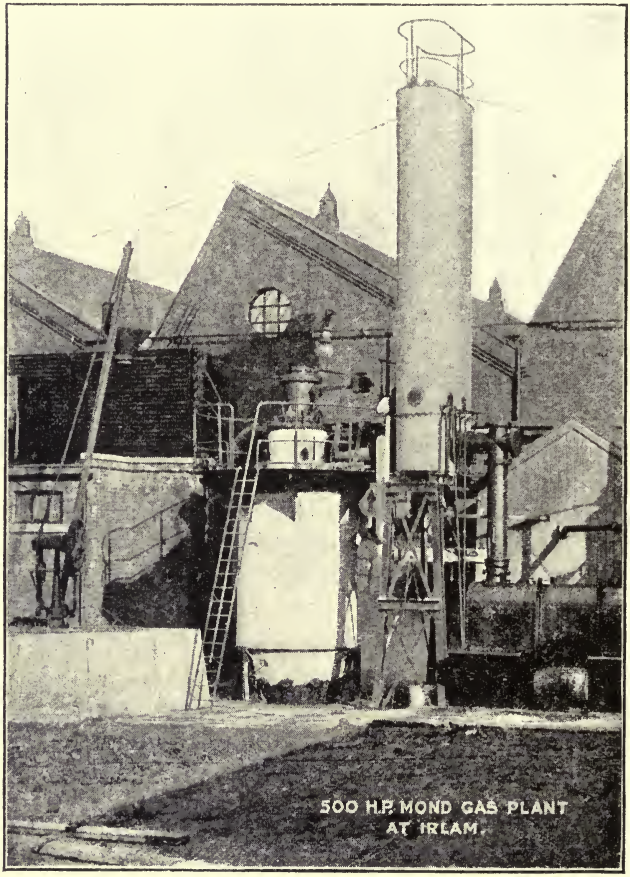

Fig. 54.—Mond gas plant at Irlam.

at a lower level where combustion is taking place. In others, again, an attempt is made to arrange the grate, the feeding hopper, and the gas outlet so that the tarry vapours distilled off from the raw fuel must pass through heated fuel before they reach the gas outlet, while the fuel itself must become coked before it reaches the zone where combustion is taking place. In producers of these

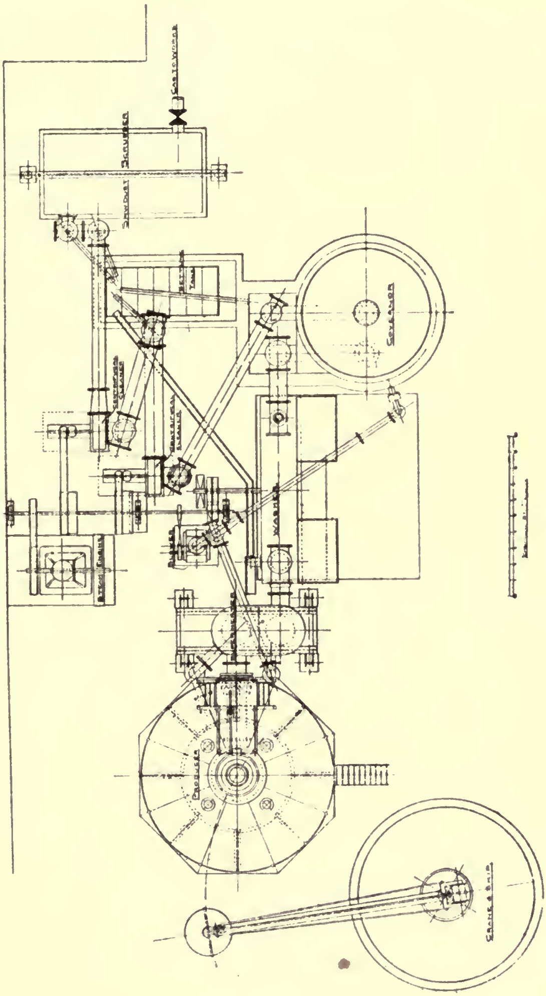

Fig. 55.—Plan of Mond gas plant at Irlam.

types the conversion of the tarry vapours into fixed gas is not complete, and there is a certain quantity of tar in the gas, which must be removed by scrubbing.

Another method of fixing the tarry vapours is to work the producer with a down-draught instead of an up-draught. The principle is to free the raw fuel from tarry vapours, and compel the latter to traverse the whole depth of the fire, so that they may be converted into fixed gases. It is difficult to carry this out effectually in practice, owing to the difficulty of maintaining a suitable temperature. If the temperature of the fire is too low not all the tarry vapours are decomposed; on the other hand, if it is too high all the tarry vapours are decomposed, but carbon is liberated in the form of very fine soot, and the removal of this from the gas is troublesome. M. Deschamps, of Paris, works his producer with a down-draught, and he makes a special point of letting air mix freely with the tarry vapours before they pass through the incandescent fuel. He claims that in this way they are converted to carbon monoxide and hydrogen, and that the gas is free from both tar and soot.

The principle of working a producer downwards was tried so long ago as 1866 (for furnace work) by Howson, of Middlesborough.[1] He used air at pressure, forced in by a steam-jet injector, but Deschamps works his producer downwards by suction from a fan or gas-engine, and this combination has several practical advantages. The producer can be permanently open at the top, and there is no smoke given off while coal is being put in, as the suction draws all the smoke downwards through the fire. With many plants worked by pressure the smoke nuisance is a serious one. With downward working there is no difficulty in poking down through the fuel, and this is a great advantage in any plant in which bituminous coal is used, as the fire has a tendency to burn hollow, especially if the coal is of a caking kind. With downward working the clinker difficulties are also considerably reduced. Having mentioned these advantages, we must point out some drawbacks which this system involves. It is difficult to burn the fuel completely, and usually there is an accumulation of small carbon in the lower part of the producer. This chokes the

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[1] *Proc. Inst. C.E.*, 1886, vol. lxxxiv. pp. 42, 68.

interstices through which the currents of gas have to pass, and adds considerably to the resistance which the suction of the fan or engine has to overcome. This in turn affects the quality of the gas produced, because the currents of air are not then distributed evenly through the fire.

To avoid these and other difficulties Mr. Dowson patented, in 1903, a producer of which the upper part is worked with a down-draught and the lower part with an up-draught, the gas outlet being midway between the upper and lower portions. Preferably the producer is worked by suction, the raw coal being introduced at the top; the hydrocarbon vapours which are distilled off in the upper part of the producer pass downward through incandescent fuel and are either burnt with air or are converted into fixed gases. As the fuel burns away, the coke which is formed in the upper part of the producer gradually sinks into the lower part and there meets air, or steam and air, passing upwards, and ordinary producer gas is formed. The burning of fuel in the lower portion of the producer helps to maintain the required temperature, and gives the necessary relief to the fire in the upper portion, thus preventing an abnormal increase in the resistance.

Recently MM. Fichet & Heurtey of Paris have been working on somewhat similar lines. We have seen a plant of theirs working well with semi-bituminous coal containing 11·5 per cent. of volatile matter, but we have not seen one working with bituminous coal such as we have to deal with in this country.

MM. Boutillier et Cie have a producer in which the raw fuel is forced on a grate or table at the bottom of the fire, and as the producer is worked with an up-draught from a blower the tarry vapours distilled off from the raw fuel at the bottom ascend through the incandescent fuel above. An incidental advantage of this arrangement is that although there is an up-draught the depth of the fire can always be the same, provided the feed is regulated to suit the rate of consumption, which varies when the load on the engine varies. We have seen a plant of this type working well with semi-bituminous Belgian coal containing 13 per cent. of volatile matter.

Another system which has been tried is a modification of the water-gas plant described in Chapter IV. In this there are two producers, one of which is worked upwards, the other downwards. After the fires in both the producers have been blown up with air, the gases and vapours formed in the upward-working producer are passed downwards through the other producer. This causes a lowering of temperature in the latter, so that after a short run the fire in this producer has to be blown up again with air. The system is therefore intermittent, and the quality of the gas varies considerably; to equalise this, one gasholder at least must be used. In the Loomis-Pettibone plant (United States), which is the most modern and successful of this type, there are two gasholders.

If we take a general survey of this branch of the subject, it will be seen that many different processes and many types of plant are being tried for making from bituminous coal gas which is suitable for engine work. When anthracite or coke is to be used the choice lies between working by pressure or by suction, according to the requirements of each case; and when once this choice has been made the principles to be followed in the construction and working of the plant are well defined. But for the present the methods of working with bituminous coal are tentative and it cannot be said that any of the plants now used are as simple and as free from trouble as those working with anthracite or coke. The use of bituminous coal is, in fact, beset with difficulties, and as it has been tried for engine work for such a short time, it is not surprising that no more has been accomplished. In course of time the best lines to follow will doubtless be discovered.

In conclusion, we may say that, speaking generally, caking coals are not suitable for gas-producers, and that this is specially the case when the gas is to be used for engines. If the coal cakes there is a hollow, instead of a close, dense fire, so that the gases are not brought properly into contact with the hot fuel, and inferior gas is made. Even with non-caking bituminous coals the fire should be poked occasionally, especially with producers of moderate size, to ensure that gas of uniform quality will be made. This means that there must be a fireman in constant attendance; and in a plant for less than 200 B.H.P.—and sometimes for a plant of larger size —it may be taken that the cost of wages for a bituminous plant will usually exceed the difference in cost of bituminous coal compared with that of small anthracite or gas-coke used in a suction plant. It is, therefore, generally recognised that with gas-plants as they are now made it will not pay to use bituminous coal for a smaller size than that required for 200 or even 300 B.H.P. Another reason for constant attention is that there are several mechanical appliances to keep in good running order, such as the blower and its engine, the high-speed centrifugal tar extractors, and in most cases a steam-boiler.

CHAPTER X

STAND-BY LOSSES

Close attention is usually given to the consumption of fuel per horse-power-hour while a gas plant is serving an engine, sometimes to the thousandth of a pound, and it is not a little remarkable that account is seldom taken of the consumption of fuel while a producer is standing with a fire in it. It is exceedingly low compared with that of a steam-boiler under like conditions. So long ago as 1886 Mr. Dowson made an interesting test with a small set of his plant, capable of serving a maximum of about 30 B.H.P.[1] The gas producer and the little boiler which gave it the steam required were placed on a weighing-machine, as shown in Fig. 56. The outlet pipe from the producer had a loose water joint perfectly free, so that the weighing-machine could go up or down while gas was made continuously and conveyed to the engine. The chief object of this arrangement was to determine accurately not only the total consumption of fuel and water, but the weight of these materials converted into mechanical work at stated times. A separate test was made to determine the stand-by loss in the producer after the engine was stopped. The fire in the little boiler was raked out at the end of the day's run, as was usual in ordinary work; but the gas producer, with an anthracite fire in it, was allowed to stand eighteen hours, and during that time the actual loss of fuel was only 18 lbs., or 1 lb. per hour. The plant stood in an open yard without shelter of any kind, and the test was made in the month of November when the day temperature was about 7° C. It was doubtless lower during the night.

In 1893 Messrs. Crossley of Openshaw, who were using a Dowson gas-producer for about 250 H.P., reported that on January 20th the working of the producer was stopped at 8 p.m., and that

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[1] *Proc. Inst. C.E.*, 1893, vol. cxii. p. 88.

it was started again at 5 a.m. the next day. The waste of fuel during this stoppage was at the rate of 5·1 lbs. per hour. On January 21st (Saturday), the producer was stopped at 2 p.m., and it was started again at 7 a.m. on the 23rd (Monday); the waste was at the rate of 3·9 lbs. per hour. In all these tests a slight current of air was allowed to pass through the producer during the stand-by hours to keep the fire alight, and as this current was not constant the waste of fuel necessarily varied somewhat, but the periods of standing were long so that the averages given are trustworthy.

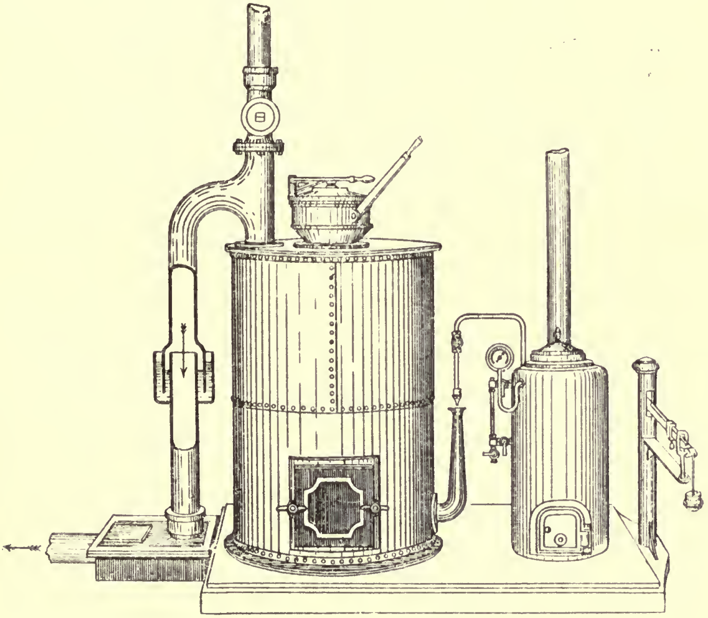

Fig. 56.—Gas producer on weighing-machine.

Being anxious to compare these results with the stand-by losses of steam boilers, Mr. Dowson consulted the late Mr. Bryan Donkin in 1898, and the latter made some special tests with a Lancashire boiler at his works. He reported that the boiler had about 580 square feet of heating surface, that it was carefully set in brickwork in the usual way, and that it would evaporate economically (from cold) 250 to 300 gallons of water per hour. The two fires of the boiler were banked about 5.30 p.m., and the fireman came again at 5 a.m. the next morning to make up the fires. When the two fires of the boiler were banked, the fireman put on each fire about 3 cwts. of small coal, making 672 lbs. in all. Mr. Donkin estimated that 150 lbs. of this coal were actually consumed during the night, but he did not know to what extent the remaining 522 lbs. were affected by being subjected to heat for several hours. He added that during the stand-by hours the brickwork was cooled considerably, and that when the fires were made up in the morning the brickwork was heated again at the expense of additional fuel.

More recently (1904) Mr. Dowson interested several engineers in the subject, and they were good enough to have special tests made for him. The following are the results they gave:—

Leicester.—At this place there is a gas plant which serves gas-engines for the electric lighting of the railway-station and goods yard, and Mr. Deeley, the locomotive superintendent of the Midland Railway, wrote as follows:—

"A twenty-four hours' trial has been made at Leicester, and it is found that the amount of coal required to leave the generator [100 B.H.P.] in the same state at the end of the twenty-four hours as it was at the beginning, was 51 lbs., or 2·1 lbs. per hour, and at the end of this period gas was passed into the gasholder (ready for use) in ten minutes. A steam boiler of the same horse-power, under the same conditions, requires 14 lbs. of coal per hour to maintain its pressure ready for immediate use."

Birmingham.—Mr. Henry Lea, consulting engineer, had a special test made of a Lancashire boiler 28 ft. long by 7 ft. 6 ins. diameter, with two flues each 3 ft. diameter. He reported that the evaporative power in full work was 8000 to 9000 lbs. of water per hour. The consumption of Cannock screened coal in the boiler while standing twelve hours was about 4 cwts. During this time the steam pressure fell from 120 lbs. to 90 lbs., and it was not raised again to 120 lbs. The consumption while standing was 37·5 lbs. per hour.

Chelmsford.—Colonel R. E. B. Crompton sent the following report from one of his staff:—

"Although we have never made a special test for the particular purpose in question, we have found that to keep up one of our hand-fired Babcock & Wilcox boilers hot and ready for steam at short notice, during a period of about ten hours, required about 6 cwts. of hard steam coal or thereabouts. Under the above conditions, the boiler would be coupled to the main steam range, *i.e.* not isolated. The rating of the boiler is 4200 lbs. per hour, and the coal used is Shipley best hards.

"I called at the Chelmsford Electric Light Co.'s station, to see if I could obtain any figures on the subject, as they practically always have one boiler banked up during the day, and they tell me that they use about 3 cwt. on a similar boiler to ours, but with chain-grate stoker; and under similar conditions, during about ten hours, it took another 3 cwt. to make the boiler begin to generate steam. The coal used in this case would be Shipley peas."

In both these cases the consumption was 67 lbs. per standing hour.

London.—Sir Alexander Kennedy wrote: "What I have repeatedly measured is the proportion borne by the coal actually used at a generating station, in boilers of which the stop-valves are closed, to the total coal used in the same time in the station. I have found that during the heavy hours of working in an electric lighting station, *i.e.* from 3 to 11 p.m., this proportion is about 2½ per cent. Measured over the whole twenty-four hours' load in one case, I found it to amount to 7·2 per cent. for a fortnight; in another case 7·8 per cent. At other times over forty-eight or seventy-two hours I have found it to average 10 per cent. All these higher figures are for cases where a very large number of boilers have to be kept or got ready for a very short peak."

This information is interesting in itself, but it does not enable us to arrive at the stand-by loss of an individual boiler.

Newport (Mon.).—Mr. H. Collings Bishop, the borough electrical engineer, made two special tests, and reported as follows:—

Trial No. 1.—With two Babcock & Wilcox boilers of 500 H.P. each, the consumption of Welsh coal (colliery screenings) during five hours standing was 1800 lbs. The steam pressure at the beginning of the test was 120 lbs.; it dropped to 80 lbs. during the test, and was raised to 120 lbs. at the finish. The consumption of coal was about 180 lbs. per boiler per hour.

Trial No. 2.—The same two boilers at a week end while standing twenty-nine hours consumed 6500 lbs. of coal. The steam pressure at the start was 120 lbs.; it fell to 50 lbs., and was raised to 120 lbs. at the finish. The consumption of coal was about 112 lbs. per boiler per hour.

Rugby.—Messrs. Willans & Robinson also made a special test with a Niclaussé type of boiler, capable of evaporating 8000 lbs. of water per hour; its dimensions were 13 ft. × 10 ft. × 10 ft. They gave the consumption of Midland large coal as 600 lbs. while standing twelve hours, the full steam pressure and water-level being maintained throughout the trial. This consumption was equal to 50 lbs. per standing hour.

London.—Mr. F. A. Wilkinson, electrical engineer, had a special test made with a Lancashire boiler (Galloway) 30 ft. long by 9 ft. diameter, with a grate area of 47·5 sq. ft. This boiler was one of a battery; on one side there was a similar boiler doing regular work, and on the other side a similar boiler which had been shut down for some months. The fires were cleaned just before the start and again at the end of the test. There was a Musgrave superheater at the end of the boiler, and the valve between the range of boilers and the superheater was closed. There was a slight leakage at the deadweight valve throughout the test, and a certain amount of water escaped through the trap which drains the superheater connections. The water in the gauge glass fell ¾ in. during the trial. The consumption of coal during twelve hours standing was 537 lbs. = 44·7 lbs. per hour.

Smallheath.—At this place there is a large gas plant in the works of the Birmingham Small Arms Co. One set of 250 B.H.P. was tested by Mr. Henry Lea, their consulting engineer, during five consecutive days. The consumption of anthracite peas during the stand-by hours was at the average rate of 4·5 lbs. per hour.

Limerick.—The corporation of Limerick have a gas plant for the electric light station, and when the consulting engineer, Mr. J. Enright, tested the plant it was found that the stand-by loss in a 225 B.H.P. producer was at the rate of 3·8 lbs. per hour.

Walthamstow.—There is a large gas power installation at this place (over 3000 B.H.P.) for the electric lighting and tramway service, and Mr. F. A. Wilkinson, the electrical engineer in charge, wrote: "I have made some tests on the gas generators installed at these works to ascertain the actual consumption of anthracite in a gas generator when standing with a fire in it, and when gas was not being made. A 375 B.H.P. generator was standing forty-eight hours, and the total weight of coal consumed was 84 lbs." This is equal to only 1·8 lb. per hour.

We give a *résumé* of these results in the following table, and may explain that for estimating the maximum horse-power of the boilers we have allowed 20 lbs. of water per horse-power-hour.

Table XVI.—Consumption of Fuel in Stand-by Hours.

Steam Power.

Type of boiler.	Max. H.P. of boiler.	Coal consumed per standing hour.	Authority.
1. Various	100	14·0 lbs.	Mr. Deeley, Loco.-Supt., Midland Railway.
2. Lancashire	450	[1]37·5 „	Mr. H. Lea.
3. Babcock and Wilcox .	210	67·0 „	Col. R. E. B. Crompton.
4. „ „ .	210	67·0 „	„ „
5. „ „ .	500	180·0 „	Mr. H. Collings Bishop.
6. „ „ .	500	112·0 „	„ „ „
7. Niclaussé	400	50·0 „	Messrs. Willans and Robinson.
8. Lancashire	400	44·7 „	Mr. F. A. Wilkinson.
	Average . .	71·5 lbs.	

Table XVII.—Consumption of Fuel in Stand-by Hours.

Gas Power.

Locality.	Max. H.P. of producer.	Coal consumed per standing hour.	Authority.
1. Openshaw	250	5·1 lbs.	Messrs. Crossley, Bros., Ltd.
2. „	250	3·9 „	„ „ „
3. Leicester	100	2·1 „	Mr. Deeley (Midland Railway).
4. Smallheath	250	4·5 „	Mr. Henry Lea.
5. Limerick	225	3·8 „	Mr. J. Enright.
6. Walthamstow . . .	375	1·8 „	Mr. F. A. Wilkinson.
	Average . .	3·5 lbs.	

[1] Exclusive of raising the steam pressure from 90 to 120 lbs.

In this table we have not included the small 30 B.H.P. producer referred to on p. 170, as all the other producers are much larger, and its small consumption might be thought to lower the general average unduly. But without considering mere fractions of a pound it is clear that the stand-by loss in a gas-producer is trifling compared with that of a steam-boiler of any type; and the explanation is not far to seek. For a given horse-power the producer is much smaller, and has far less radiating surface than a boiler; it has no water in it to be heated, and it can be worked up to its maximum production in about fifteen minutes, after standing almost any length of time. With a boiler, except in the vertical or portable type, there is a large amount of external brickwork to be heated, and there is a considerable quantity of water, even in the tubular type. When the boiler is standing, the water and the brickwork lose heat, and not only more time but more fuel is required to make up this loss than in the case of a gas-producer. Doubtless the heat efficiency of a good boiler is high when it is working to nearly its full capacity; but the reverse is the case when it is standing; and in factories and electric lighting and power stations, where the plant is usually standing a long time, this question is deserving of close attention.

By way of illustration, let us take the case of a gas plant and engine for 200 B.H.P., and of a boiler and steam-engine of the same power, each working at its maximum for eight hours and standing sixteen hours. For the gas power we will assume a fuel consumption of 1 lb. per B.H.P.-hour while the plant is working, and 3·8 lbs. per hour when standing, as at Limerick. For the steam power we will assume a fuel consumption of 2·5 lbs. per B.H.P.-hour while the plant is working, and 67 lbs. per hour when standing, as at Chelmsford. We then have the following comparative results:—

Gas power: 200 H.P. × 1 lb. × 8 hours = 1600 lbs.
3·8 lbs. × 16 hours = 61 „
Total . . 1661 „

Steam power: 200 H.P. × 2·5 lbs. × 8 hours = 4000 lbs.
67 lbs. × 16 hours = 1072 „
Total . . 5072 „

On this basis, with steam power the stand-by loss of the boiler is over 20 per cent. of the total fuel consumed in twenty-four hours; whereas with gas power the stand-by loss of the gas-producer is under 4 per cent. of the total fuel consumed in twenty-four hours.

If we were to take the case of a plant for 500 B.H.P. the result would be still more striking. For the gas power we will assume a fuel consumption of 1 lb. per B.H.P.-hour while the plant is working, and as much as 5 lbs. per hour when standing. For the steam power we will assume a fuel consumption of 2·5 lbs. per B.H.P.-hour while the plant is working, and 112 lbs. per hour when standing, taking the lower consumption of the two 500 H.P. boilers tested by Mr. Bishop. We then have the following results:—

Gas power: 500 H.P. × 1 lb. × 8 hours = 4000 lbs.
5 lbs. × 16 hours = 80 „
Total . . 4080 „

Steam power: 500 H.P. × 2·5 lbs. × 8 hours = 10,000 lbs.
112 lbs. × 16 hours = 1,792 „
Total . . 11,792 „

On this basis, with steam power the stand-by loss of the boiler is about 15 per cent. of the total fuel consumed in twenty-four hours; whereas with gas-power the stand-by loss of the gas producer is under 2 per cent. of the total fuel consumed in twenty-four hours, although the consumption during the eight working hours is only 4000 lbs., compared with 10,000 lbs. for steam power. If we take the percentage of the stand-by loss on the fuel consumed during the working hours, in each case, we have the following results:—

	200 B.H.P.	500 B.H.P.
Steam power	26·8 per cent. . .	17·9 per cent.
Gas power	3·8 „ . .	2·0 „

CHAPTER XI

COMPARISON OF GAS AND STEAM POWER

It would be beyond the scope of this little work on producer gas to enter minutely into questions affecting the gas-engine only; but the subject of gas-power cannot be considered without taking account of the heat efficiency, not only of the gas plant, but of the gas-engine also. The two are connected inseparably, as in the case of the steam-engine and boiler. We propose, therefore, to consider briefly the combined heat efficiency of a gas plant and gas-engine, and to compare it with that of a boiler and steam-engine of the same power.

For this purpose we have constructed the diagrams shown in Figs. 57, 58, 59 and 60. The first two refer to steam and gas power plants each of a size suitable for 250 B.H.P.; the other two refer to plants suitable for 40 B.H.P. each. In each the base of the diagram represents the number of heat units (calories or British) in the fuel consumed to produce the same amount of useful work, viz. the equivalent of 100 heat units.

In determining the heat efficiencies of steam-boilers we have consulted the late Mr. Bryan Donkin's work on the "Heat Efficiency of Steam Boilers" (1898). He gives the result of a large number of careful tests, and from these we get the following averages:—

Table XVIII.—Heat Efficiencies of Steam-boilers.

Description of boiler.	Number of boilers tested.	Average heat efficiency per cent.
Water tube (Babcock and Wilcox type) .	16	61·2
Lancashire	161	63·4
Water tube (various)	27	67·5
Cornish	37	67·6
Marine	32	69·0
Locomotive and Portable	36	72·4

We have also the authority of Sir Alexander Kennedy for saying that the actual heat efficiencies of steam-boilers vary from 50 to 80 per cent. He said,[1] "The 50 per cent. is the result of everyday careless working, the 80 per cent. the result of thoroughly good working with real care." For the 250 B.H.P. steam plant (Fig. 57) we have taken 80 per cent. as the heat efficiency of the boiler; and for the 40 B.H.P. size (Fig. 59) we have taken 75 per cent., although Mr. Donkin's averages show that in practice the efficiencies obtained are much lower than those we have assumed. For the heat lost by condensation in steam pipes,

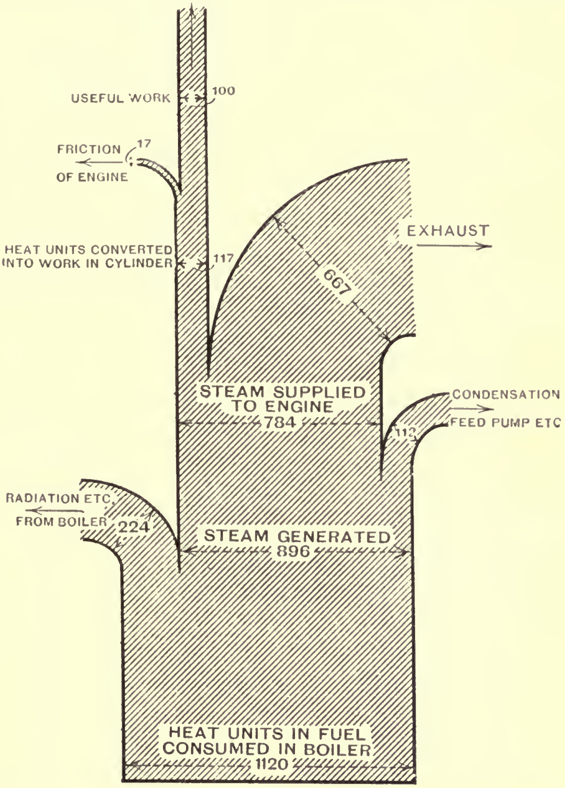

Fig. 57.—Steam power—heat efficiency diagram 250 B.H.P.

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[1] Royal Inst. Lecture, 1893.

the driving of feed pumps and other usual losses, we have taken 10 per cent. of the total heat in Fig. 57, and 5 per cent. in Fig. 59. For the 250 B.H.P. steam-engine (Fig. 57), we have assumed a heat efficiency of 15 per cent., *i.e.* 15 per cent. of the heat supplied to the cylinder is assumed to be converted into *indicated* work; for the smaller steam-engine (Fig. 59) we have assumed a heat efficiency of 10 per cent. For all the diagrams (steam and gas) we have assumed that the friction of the engine, *i.e.* the difference between the indicated horse-power and the brake horse-power, is 15 per cent. of the indicated horse-power.

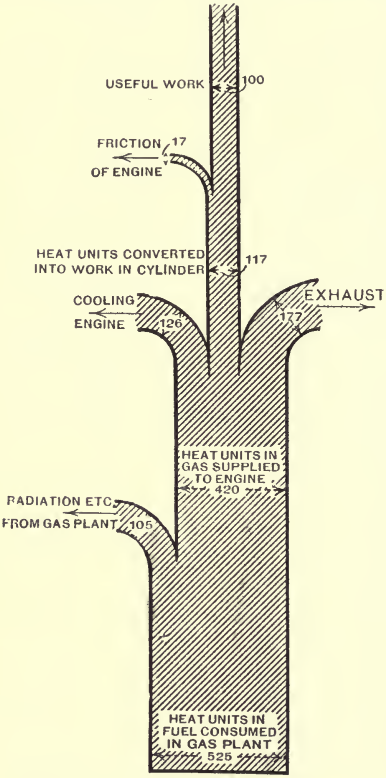

FIG. 58.—Gas power—heat efficiency diagram 250 B.H.P.

For the 250 B.H.P. gas-power diagram (Fig. 58) we have assumed that the gas plant is of the steam-jet pressure type, and that including the small boiler its heat efficiency is 80 per cent.; but if we had taken a plant of the suction type without an independent boiler (as at Chelmsford, p. 189), it would have been more correct to assume a heat efficiency of 85 per cent. For the 40 B.H.P. gas-power diagram (Fig. 60) we have assumed that the gas plant is of the suction type, and that its heat efficiency is 85 per cent., although 90 per cent. has already been attained for this size of plant (*vide ante*, p. 130). The loss of heat in converting the solid fuel into gas is therefore assumed to be 20 per cent. of the total heat of combustion of the fuel in the case of Fig. 58, and 15 per cent. in Fig. 60. With the gas plant there are no losses from condensation or other causes beyond those included in the 20 and 15 per cent. just referred to. For the gas-engines we have assumed a heat efficiency of 28 per cent.; and of the 72 per cent. lost in the engines we have apportioned 30 per cent. to the cooling, and 42 per cent. to the exhaust.[1]

These diagrams show at a glance the chief sources of waste in the two systems; and although they can only be estimated approximately, and although they vary in different cases, the figures correspond with fuel consumptions per B.H.P.-hour which are in accord with practical results for gas-power, and the figures for steam power are probably considerably better than are usually

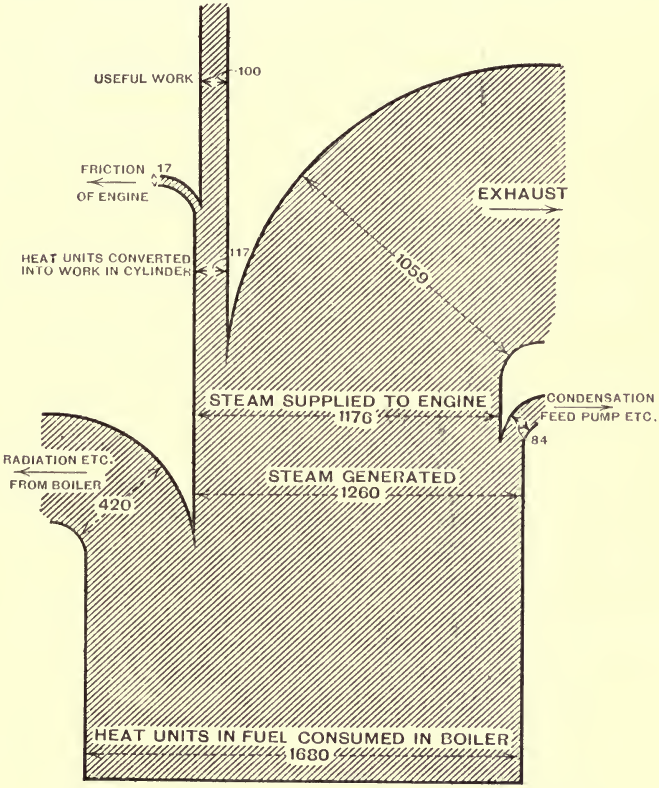

FIG. 59.—Steam power—heat efficiency diagram 40 B.H.P.

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[1] James Forrest Lecture, *Proc. Inst. C.E.*, 1904, vol. clviii. p. 283.

obtained with the sizes of installation considered. The figures correspond approximately with the following consumptions of fuel of average quality:—

900 grams (2 lbs.) per B.H.P.-hour for 250 B.H.P. steam power.
450 grams (1 lb.) „ „ „ gas power (pressure plant).
1350 grams (3 lbs.) „ „ 40 B.H.P. steam power.
400 grams (0·9 lbs.) „ „ „ gas power (suction plant).

Taking the 250 B.H.P. size, we see in Fig. 57 that of 1120 heat units in the fuel consumed in the boiler 224 are lost in ashes, radiation, flue gases, etc.; that there are 896 units in steam generated, and that 112 units in this steam are lost by condensation in pipes, feed pump, etc. The steam supplied to the engine contains 784 heat units, but of these 667 are lost in the exhaust, so that only 117 are converted into indicated work in the engine, and from this 17 have to be deducted for the friction of the latter.

In Fig. 58 we see that of 525 heat units in the fuel consumed in the gas plant 105 are lost in ashes, radiation, cooling of gas, etc.; that there are 420 units in the gas supplied to the engine, and that of these 177 are lost in the exhaust, and 126 in cooling. As in Fig. 57, there are 117 units converted into indicated work in the engine, and of these 17 are deducted for friction.

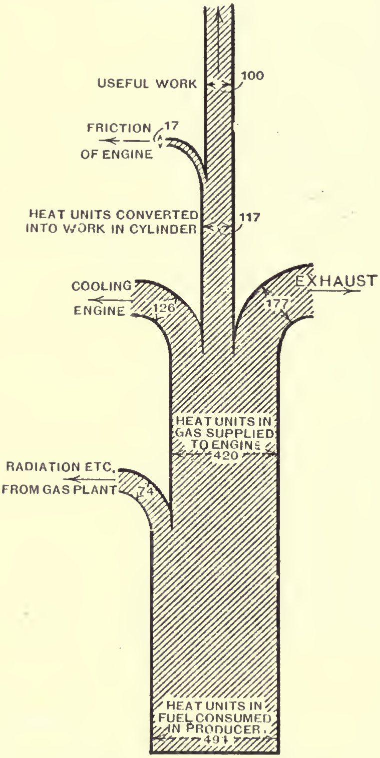

Fig. 60. – Gas power—heat efficiency diagram 40 B.H.P.

In the 40 B.H.P. size, it will be seen in Fig. 59 that, starting with 1680 heat units in the fuel consumed in the boiler, 420 are lost in ashes, radiation, flue gases, etc.; that there are 1260 units in the steam generated, of which 84 are lost by condensation in pipes, feed pump, etc. The steam supplied to the engine contains 1176 units of heat, but of these no less than 1059 are lost in the exhaust.

In Fig. 60 we see that of 494 heat units in the fuel consumed in the gas producer 74 are lost in ashes, radiation, cooling of gas, etc.; that there are 420 units in the gas supplied to the engine, and that the remaining losses are similar to those in Fig. 58.

On the above bases the general result is that for the 250 B.H.P. size, in order to obtain 100 heat units in useful work with steam power, there must be 1120 heat units in the fuel consumed in the boiler; whereas with gas power there need only be 525 units in the fuel consumed in the plant. This shows a saving in fuel of 53 per cent. in favour of the gas plant. The result is still more striking in the case of the 40 B.H.P. size, as there must be 1680 units in the fuel consumed for steam power, compared with 494 units for gas power. This is a saving of 70 per cent. in favour of the gas plant. These figures do not include any allowance for stand-by losses, although we should have preferred to give them if possible. We know what they are for gas plants of the sizes considered, but we do not know exactly what they would be for steam plants of the same powers; we may, however, safely conclude from the figures given in Tables XVI. and XVII. (p. 175) that they would be considerably greater for steam power than for gas power.

These diagrams not only help us to compare the heat efficiency of gas power with that of steam power, but they bring home to us the fact that even with a modern gas-engine there are very serious heat losses; and it may be well to consider what are its possibilities in the future compared with those of the steam-engine. It is generally conceded that theoretically the heat efficiency of the latter cannot exceed 30 per cent., and that there is no likelihood of attaining this in practice. On the other hand, the actual heat efficiency of a gas-engine has already reached the theoretical best of the steam-engine. Of still greater importance is the fact that theoretically it is possible for the gas-engine to have a much higher efficiency; what that efficiency may be cannot be precisely stated, but all authorities are agreed that there is still a large margin for practical improvements; and it is only reasonable to suppose that in the course of time the present great losses in cooling the engine, and in the exhaust, will be appreciably reduced.

Fig. 61.—Tramway and electric lighting at Walthamstow.

The above diagrams represent the heat efficiencies when the engines are working at full or nearly full load; and we should consider what would occur with a three-quarter or a half load.

It is well known that the heat efficiency of a steam-engine falls as the load diminishes, owing to the heat losses being greater in proportion to the useful work done; and this also occurs with a gas-engine. The lowering of the heat efficiency with reduced loads may not be in precisely the same proportion for gas-engines as for steam-engines, but approximately it may be assumed that the comparison we have made in the above figures will hold good, in about the same proportion, for three-quarter or half loads as for a full load. As regards the heat efficiencies of the gas-producing plant and the steam-boiler, they are not so susceptible of change as those of the engines; their principle of working is altogether different. Actually the heat efficiency of a gas plant or of a steam-boiler is about the same at a three-quarter as at the maximum output; at half load there will be some lowering of the efficiency, but it will be about the same for the gas-producer as for the steam-boiler so that on this account also our comparison will be in about the same proportion as for the full load.

We will now describe a practical example of a gas-power installation on a large scale. We refer to the generating station of the Urban District Council of Walthamstow, where the current is used for electric lighting and for driving tramway-cars (see Fig. 61). The engines are of the Westinghouse type, and are shown in Fig. 62; the gas plant is of the Dowson steam-jet type, as shown in Figs. 63 and 64. In 1901 the Council began with about 250 B.H.P.; in 1902 they added 250 and afterwards 800 B.H.P.; in 1905 they added about 1700 B.H.P., so that there is now an aggregate of about 3000 B.H.P. The following particulars are taken from the returns of working for the year ending March 31, 1906:—

Total Board of Trade units generated	2,394,850
Load factor	21 per cent.
Working cost per unit generated:—	
Coal and other fuel	0·40 penny.
Oil, waste, water, etc.	0·10 „
Wages for generation of current	0·27 „

In a test in November, 1905, the calorific power of the gas (higher scale) was 1540 calories per c.m. (173 Brit. T.U. per cubic foot) at 0° C. and 760 mm. pressure.

The consulting engineer, Mr. J. Enright, has made numerous tests, and he reported to the Council as follows: "I have satisfied

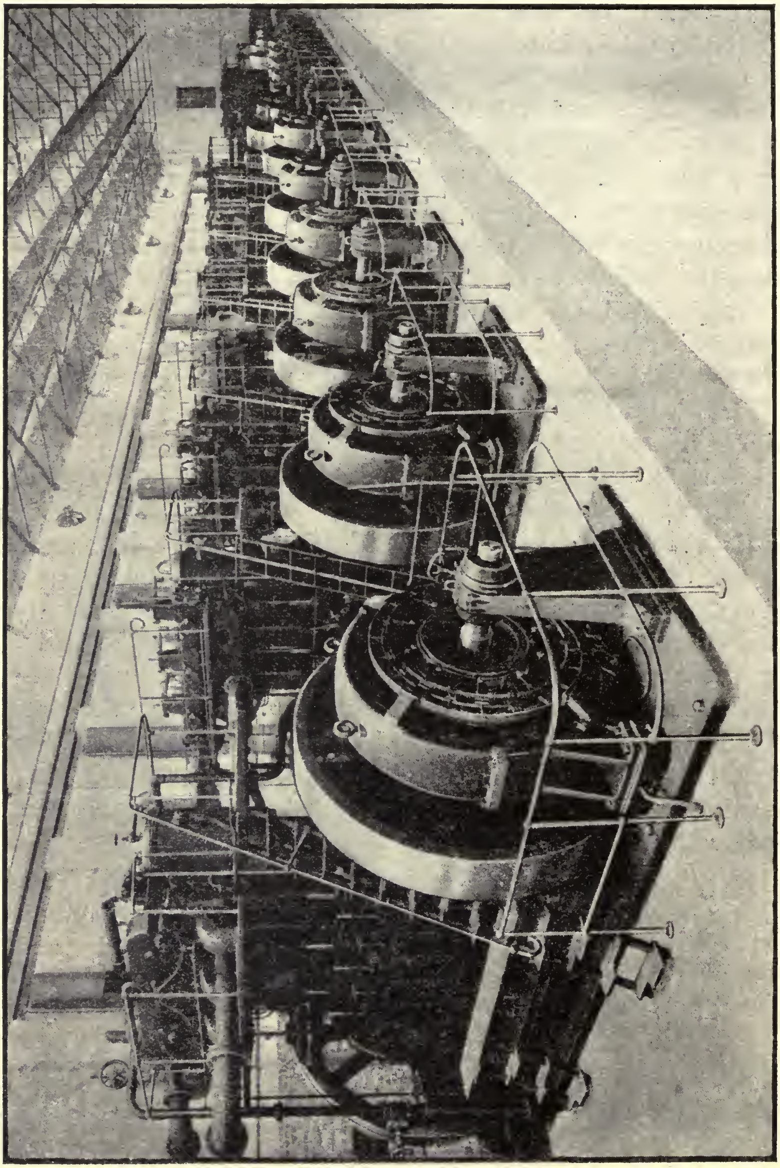

Fig. 62.—Gas engines at electric light and power station, Walthamstow.

myself that at full load the coal consumption of these engines is as nearly as possible 1 lb. per B.H.P.-hour under the conditions prevailing in an electric light station." As the gas plant is of the steam-jet type, the fuel consumption includes that used for the steam-boilers. If the plant were of the suction type this amount of fuel would be saved, and it would represent about

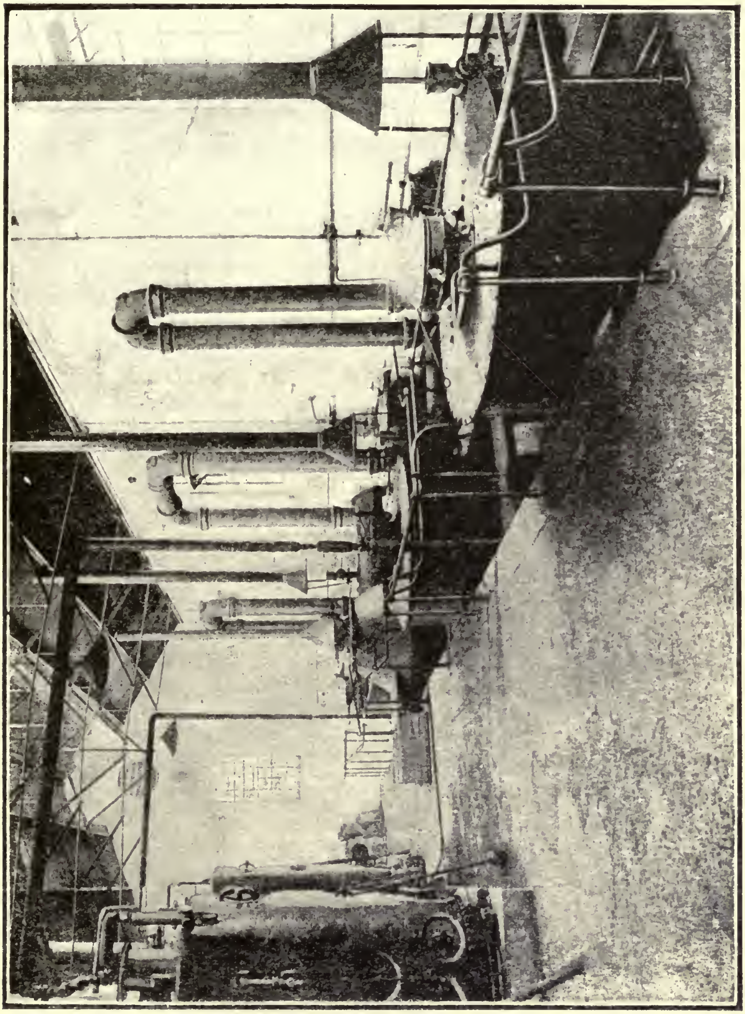

FIG 63.—Dowson gas producers at Walthamstow.

one-sixth of the whole; but as there are thirteen engines with very variable loads it is a case where a pressure plant and not a suction plant is the more convenient. In this way the mains are always charged with gas at pressure ready to be used at a

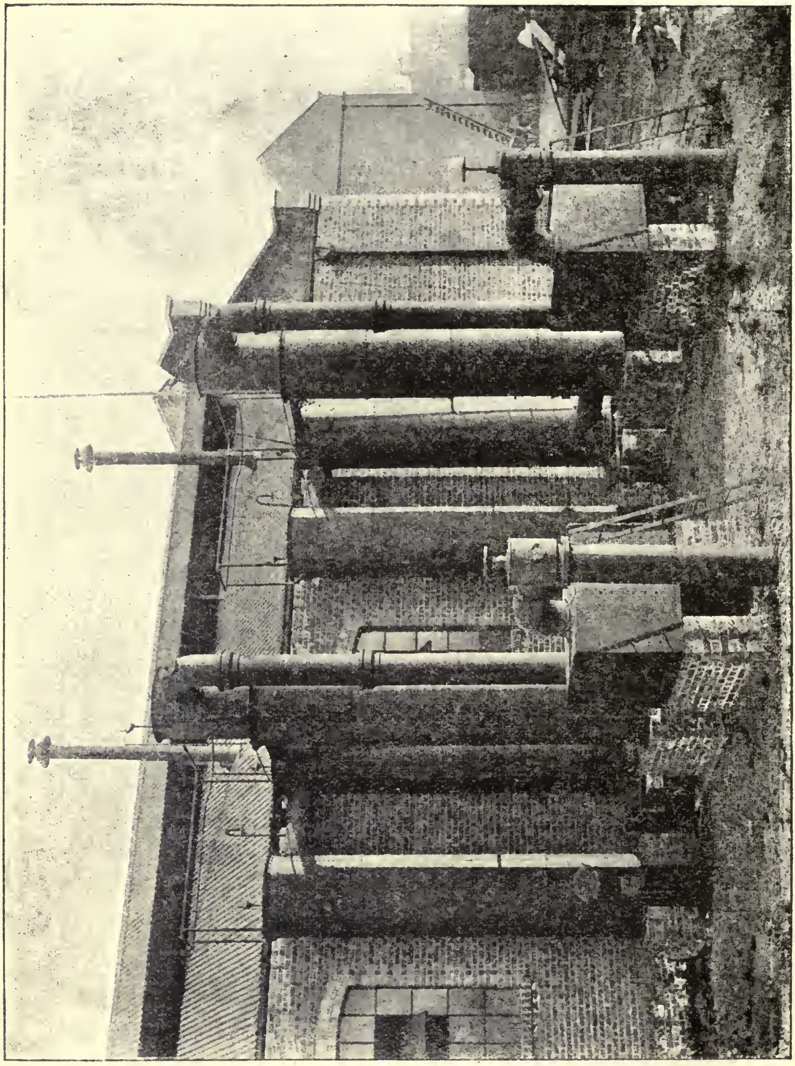

Fig. 64.—Gas scrubbers, etc., at Walthamstow.

moment's notice for any engine; and the arrangement of piping is more simple.

Another practical example which may be cited is that of the Birmingham Small Arms Factory at Smallheath. They have a gas plant of the steam-jet type suitable for fully 1500 B.H.P. if all the gas were used for power. Actually about two-thirds of the gas is used for power (the engines being of various types), and the remainder is used for various kinds of heating work. One 250 B.H.P. Westinghouse engine and one set of gas-producing plant were tested by Mr. Henry Lea, the consulting engineer; the trial lasted five consecutive days and gave the following results :—

Number of working hours during trial, 42¾.
Number of standing hours during trial, 62¼.
Total fuel consumed in gas-producer and boiler, including getting up fires each day, and including the fuel consumed in the producer during the standing hours, and all other sources of waste = 5552 kilos (12,214 lbs.).
Total Board of Trade units generated, 6339.
Total fuel consumed per Board of Trade unit generated = 876 grams (1·9 lb.).
Total water consumed in gas plant = 4·5 liters (1 gallon) per Brit. T.U. generated.
Average calorific power of gas (by calorimeter), 1477 calories per cubic meter (166 Brit. T.U. per cubic foot), at 0° C. and 760 mm. (steam condensed).
Gas made from anthracite peas, costing 20*s.* 6*d.* per ton delivered.
One kilo of anthracite gasified in the producer yielded 4·37 c.m. of gas at 0° C. and 760 mm. The corresponding consumption of gas-coke in the boiler was 0·10 kilo.

An interesting test was recently made with a 250 B.H.P. National gas-engine working with a Dowson suction plant at the works of the Hoffman Manufacturing Company at Chelmsford. The engine and plant were worked night and day for 123 hours without a stop; the engine was driving a dynamo, and readings were taken every half-hour of the current generated. The fuel used was anthracite peas, and its consumption was carefully noted. The general result was that the fuel consumption, including all sources of waste, was only 1·23 lb. per kilowatt-hour. This corresponds with 0·82 lb. per B.H.P.-hour developed by the engine, if the efficiency of the dynamo be taken at 90 per cent.

The following results obtained with Crossley gas-engines and suction plants are taken from a paper by Mr. T. Rigby:[1]—

Milford-on-Sea.—Plant for maximum of 25 kilowatts.
  Flying start: duration of test, 3 hours 49 minutes.
  Average load on dynamo, 23·62 kilowatts.
  Anthracite consumed during test, 670 grams (1·48 lb.) per kilowatt-hour.
  Calorific power of anthracite, 8275 calories per kilo (14,895 Brit. T.U. per pound).
    (Note.—It is stated that the fuel consumption when running averages 1·54 lb., and, including all stand-by losses, 2·24 lbs. per unit generated.)

Openshaw.—Plant for maximum of 60 kilowatts.
  Flying start: duration of test, 6 hours.
  Average load on dynamo, 61·4 kilowatts.
  Coke consumed during test, 598 grams (1·32 lb.) per kilowatt hour.
  Calorific power of coke, 6896 calories per kilo (12,411 Brit. T.U. per pound).

Dollar, N.B.—Plant for maximum of 18 kilowatts.
  Flying start: duration of test, 7½ hours.
  Average load on dynamo, 16·8 kilowatts.
  Anthracite consumed during test, 584 grams (1·29 lb.) per kilowatt-hour.
  Calorific power of anthracite, 8410 calories per kilo (15,138 Brit. T.U. per pound).

An important feature connected with gas power is that the producer gas, if it has been cooled and scrubbed, can be conveyed any reasonable distance in pipes without appreciable change or deterioration. If the gas is properly cooled and cleaned in the gas plant there is nothing which can be condensed except water-vapour, and if any of this is thrown down and drained away in the pipes, it is advantageous so far as the gas is concerned. In Chapter IX. we have referred specially to the distribution of producer gas under a high pressure in an extended district; but for the ordinary distribution of such gas in a factory or power station the pressure of the gas in the mains need not exceed that of a column of water 40 to 50 mm. high (say 1½ to 2 ins.). As an example, this pressure is not exceeded in the installation in Holland, illustrated on p. 93, although the gas plant is about

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[1] *Trans. Manchester Association of Engineers*, 1905.

500 meters from the factory. With such a low pressure it is easy to provide against leaks from the distributing pipes.

For gas power there is no advantage in having a higher gas pressure near the engine than that stated above; but with steam power the conditions are altogether different. With the steam-engine it is essential that the working fluid should be at high pressure when it enters the cylinder; and the steam in the pipes between the boiler and the engine cannot be at a lower pressure than the initial pressure required in the cylinder. Actually the boiler pressure is usually about 5 lbs. higher than the pressure of the steam when it reaches the engine, where the boiler and engine are not far apart. If the pressure in the pipes is only 3 to 6 atmospheres (45 to 90 lbs. per square inch) it is from 800 to 1600 times greater than that of the gas from a pressure plant; in practice the steam pressure used is sometimes as high as 9 or 10 atmospheres. The conveyance of steam at these pressures is troublesome on account of leaks, but its most serious drawback is the loss from condensation, especially if the distance it has to travel is great. In large works and in shipyards the loss from condensation alone doubles or trebles the consumption of fuel required for the boiler; moreover it is often difficult to get steam to a distant engine at the pressure required, and as the steam loses heat in the pipes a further difficulty is experienced in removing the condensed moisture from it. With gas there is no such loss, because it enters the cylinder cold, and only when the gas is in the cylinder are high temperatures and pressures developed.

When steam power is used in a mill or factory one large engine is often placed near the boiler-house to minimise the loss from condensation in the steam-pipes. If the machines to be driven are far from the engine there must necessarily be an extensive system of shafting to transmit the power, and this is not only costly but it absorbs a great deal of power. With gas power there may be several engines if it is more convenient or advantageous to subdivide the power, and there need be only one light shaft for each engine.

A further practical question is the cost of repairs and maintenance. Speaking with many years' experience, we can say that the following may be taken as a fair allowance for the repairs and maintenance (exclusive of painting) of a well-designed steam-jet gas plant :—

For	100	B.H.P. plant,	about	£4	per annum.
„	200	„	„	£6	„
„	300	„	„	£9	„
„	400	„	„	£12	„
„	500	„	„	£15	„

We will not attempt to estimate the repairs and maintenance of boilers for steam power, but there cannot be any doubt that on the same scale of working these charges are much greater. Suction plants have not been in use many years, but it is fair to assume that their cost for repairs and maintenance will be considerably less than that of steam-jet plants.

With a steam-jet pressure plant the cost of wages is about the same as for a steam plant of the same horse-power; but with a suction plant the cost of wages is much less. The consumption of water is also considerably less for gas than for steam power.

As regards the cost of fuel, we have seen that with a gas plant the consumption is about 450 grams (1 lb.) of anthracite per B.H.P.-hour: the makers of gas-engines and plants now guarantee this result. In many places the price of anthracite is about the same as that of good steam coal; but where anthracite is too dear to be economical ordinary gas coke can be used, as already mentioned in the preceding chapter.

CHAPTER XII

FUEL

A GREAT variety of fuels can be used for making producer gas, the particular kind selected depending on the type of producer, the purpose for which the gas is to be used, and the sources of supply which are available, as well as upon considerations of price.

In this country, for furnace work the majority of producers are fired with bituminous or semi-bituminous coal; on the Continent brown coal or lignite is largely used, and in some cases peat. There are also a few cases where, owing to special local circumstances, wood is used as the fuel.

When the gas is to be used in small burners for heating work, or when it is to be used for driving gas-engines, it is simplest and best to use anthracite or coke; but in some localities these are too costly for use on a large scale. As a matter of fact, nearly all plants for powers of 100 B.H.P. or less, and many plants for much larger powers, are worked with anthracite or coke, as there is then little or no trouble with tar and less labour is required than with bituminous coal or other fuels which give a tarry gas requiring careful purification. This is especially the case with the modern suction plant, which requires very little attention if anthracite or coke is used. For a large plant of the Mond, Wilson, or Mason type bituminous coal can of course be employed; but when the ammonia is to be recovered it is essential that the coal should contain a high percentage of nitrogen.

The principal constituents of each of the natural fuels mentioned above are the elements carbon, hydrogen, and oxygen; but the proportions in which they are present vary considerably in the different classes of fuel. Usually there are also small quantities of nitrogen and sulphur; and there are varying quantities of ash (consisting of the mineral constituents of the fuel), which is left as an incombustible residue when the fuel is burnt. Both the quantity and composition of the ash are very different, even in different specimens of the same class of fuel; and in considering the average composition of the different kinds of fuel it is best to deal with the combustible matter only, or, in other words, to reckon the percentages on the weight of fuel considered as dry and free from ash. In round numbers, the average composition of the different fuels used for making producer gas is indicated in Table XIX., where that of cellulose is also given.

TABLE XIX.—AVERAGE COMPOSITION OF FUELS.

	Composition of fuel, reckoned as dry and free from ash.[1]				Fuel allowed to dry in air.	
	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Moisture.	Ash.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Anthracite . .	95·0	2·5	2·5	Traces.	1 to 8	2·0 to 15
Common coal .	82·0	5·0	12·0	1·0	2 to 8	2·0 to 30
Brown coal . .	70·0	5·0	24·5	0·5	10 to 30	1·0 to 50
Peat	59·0	6·0	32·5	0·5	20 to 35	1·0 to 50
Wood . . .	50·0	6·0	43·0	1·0	10 to 20	0·5 to 4
Cellulose . .	44·4	6·2	49·4	—	—	—

The deposits of coal with which we are familiar have been formed from the *débris* of plant life by the combined influence of pressure, heat and moisture extended over an enormous period of time. Brown coal and peat have been formed in a similar manner, but the changes are not so far advanced.

The chief constituent of vegetable fibre is *cellulose,* a substance consisting of carbon, hydrogen and oxygen in the proportions indicated in Table XIX. Young fibre consists almost entirely of cellulose, but during the life of the plant about half of this is changed into *lignine,* a substance containing more carbon and less hydrogen and oxygen than cellulose. It is probable that the wood-fibre consisting of lignine and cellulose is gradually decomposed by natural decay, with the formation of water, carbon dioxide and methane. As a result of this, the proportion of carbon increases and the proportions of hydrogen and oxygen (more particularly

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[1] "Fuel and Water," Schwackhöfer and Browne, p. 41.

the latter) decrease. The ultimate product of these changes is probably graphite, which consists of almost pure carbon; and intermediate between this and wood we have the different classes of fuel which have occupied longer or shorter periods of time in their formation. Thus peat is of more recent formation than coal, and it has not lost the fibrous structure characteristic of the material from which it has been formed. It contains about 15 per cent. more carbon than cellulose. Brown coal contains about 10 per cent. more carbon than peat; it is of older formation, though sometimes the signs of its vegetable origin can be observed. Common coal and anthracite coal are the products of still further change, and the latter approximates in its composition to pure carbon.

In a sense, therefore, these fuels are the products of successive steps in the slow decomposition of vegetable matter, and it is often difficult to draw a sharp dividing line between them. It must be remembered, however, that they are derived from very different forms of plant life, and that the conditions under which the decomposition has taken place may have been very different in the various cases.

All these fuels, when heated under conditions which prevent the access of air, lose nearly the whole of their oxygen and hydrogen as well as a part of their carbon, and leave a residue consisting almost wholly of carbon and ash. This process is carried out commercially with wood, peat and common coal, and the carbonaceous residues which are obtained are known as wood-charcoal, peat-charcoal and coke respectively. The last is frequently employed in gas-producers and must be added to the list of fuels with which we have to deal.

Wood.—Different kinds of wood, when dry, have approximately the same chemical composition; but the specific gravity varies considerably. The average figures for several kinds of wood are given in Table XX., p. 196.

The amount of moisture held by the wood is very variable; it is greatest in freshly felled timber, and is greater in young wood than in old. It depends also upon the season in which the tree is felled, and may vary from 25 to 60 per cent. If the bark is removed and the wood left in the open air much of this water will evaporate, and the quantity held by the wood will eventually be reduced to 10 or 20 per cent. The wood is then said to be "air-dried."

TABLE XX.—AVERAGE COMPOSITION OF DRY WOOD.

	Specific gravity.		Moisture in freshly felled wood per cent.	Ash in undried wood per cent.	Composition of organic matter per cent.		
	Freshly felled.	Dry.			Carbon.	Hydrogen.	Oxygen and nitrogen.
Oak . . .	0·973	0·785	35·4	1·65	50·0	6·1	43·9
Beech . .	0·980	0·721	39·7	1·06	49·5	6·1	44·4
Pine . . .	0·908	0·613	39·7	1·04	50·7	6·2	43·1
Fir . . .	0·894	0·600	37·1	1·02	50·9	6·3	42·8
Birch . . .	0·919	0·664	30·8	0·85	49·6	6·3	44·1
Willow . .	0·785	0·461	26·0	2·00	50·6	6·3	43·1
Elm . . .	0·909	0·619	44·5	—	50·2	6·4	43·4
Ash . . .	0·852	0·692	28·7	—	—	—	—
Poplar . .	0·857	0·472	51·8	—	50·6	6·3	43·1

The calorific power of air-dried wood is from 3000 to 3500 calories per kilo (5400 to 6300 Brit. T.U. per pound), according to the amount of moisture it contains. When free from moisture, the calorific power would not be more than 4000 calories per kilo (7200 Brit. T.U. per pound). Wood is not very suitable for use in gas producers on account of its comparatively low calorific power. For a given amount of heat the quantity of fuel required is great, and as wood is bulky compared with an equal weight of coal or coke the amount of labour required in handling it is much greater. On account of the large quantity of volatile products formed when wood is heated, and the comparatively small amount of non-volatile carbonaceous residue, it can only be successfully employed in special producers; in practice, it is only employed when no other fuel is available.

Wood-charcoal.—This substance is usually obtained by the following process:—Wood is stacked in large heaps, which are covered with earth and charcoal dust to prevent access of air; suitable draught holes are made and the wood is ignited, the draught of air being regulated so that sufficient heat is generated to drive off the volatile matter from the wood, leaving unburnt carbon in the form of wood-charcoal. The yield of charcoal by this method is from 20 to 25 per cent. of the weight of wood employed. The volatile matter which is expelled includes the gases carbon dioxide, carbon monoxide, hydrogen and methane, together with tarry vapours and an aqueous distillate (pyroligneous acid) from which methyl alcohol, acetone and acetic acid can be obtained. When the product sought is charcoal the process described above is used and the volatile products are wasted; but wood is also carbonised in order to obtain the methyl alcohol, acetone and acetic acid, and in this case the heating is carried out in retorts in which the charcoal remains as a by-product of the process. In some instances the mixture of gases which is obtained by heating wood in retorts has been used as an illuminant, under the name of wood-gas.

Wood-charcoal retains the shape of the original pieces of wood; these, however, suffer a shrinkage in bulk of 30 to 40 per cent. It is very porous and extremely light, the specific gravity ranging from 0·17 to 0·24. The chemical composition of wood charcoal varies between the following limits:[1]—

Carbon	85 to 90	per cent.
Hydrogen	1 to 2	,,
Oxygen	2 to 4	,,
Ash	2 to 5	,,
Moisture	2 to 10	,,

Its average calorific power is 7000 calories per kilo, or 12,600 Brit. T.U. per pound. Its calorific power is therefore nearly as high as that of anthracite, and it contains little or no volatile matter; it is extremely porous and reacts readily with gases; and the ash which it contains is small in amount and does not easily fuse into clinker. Were it not for its extreme lightness wood-charcoal would be exceptionally well suited for use in gas producers; usually, however, it is too costly to compete with anthracite or coke for the purpose, although it has been suggested as a suitable fuel for a suction plant used in connection with a motor vehicle.

Peat.—As might be expected in view of its comparatively recent origin, peat is found at the surface of the earth, and the beds of peat are not covered with other and more recent strata, as is the case with the different kinds of coal.

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[1] "Fuel and Water," Schwackhöfer and Browne, p. 53.

The peat bogs or mosses, as they are called, vary in depth from only a few feet up to 20 or 30 feet. They rest on a subsoil which, either from its impervious character or from its position below the standing water-level, keeps them always more or less saturated with water.

The chief deposits of peat in the United Kingdom are to be found in Ireland, where the area of thick peat-beds (20 to 30 feet in depth) is estimated at about 2500 square miles; besides these there are some 2000 square miles of shallow deposits. Peat is also found in considerable quantities, and is extensively used, in many European countries and in Canada.

In its natural state peat contains a very large proportion of water, often as much as 90 per cent., and is quite useless as a fuel without some preliminary treatment. If the peat is cut into blocks and stacked in open formation under cover for from four to eight weeks, the amount of moisture is reduced to 25 or 30 per cent. For many purposes a drier and denser fuel, which can be handled without crumbling to pieces, is required. In many places on the Continent the peat is dried by heat, or the excess of moisture is forced out by pressure; but these operations add considerably to the cost.

The physical characteristics of peat vary considerably according to the locality and the extent to which decomposition has proceeded. Some kinds of peat are extremely fibrous and contain twigs of practically unchanged wood. Other varieties are comparatively dense and are almost without structure. When dried in air the specific gravity of peat (determined by weighing it in water) is from 0·15 to 1·0, the fibrous peat being very light. The low specific gravity given by fibrous peat is not the true value, for the peat holds a considerable quantity of air, even when it is immersed in water. If the test piece be left in water for several days, the apparent specific gravity rises. Thus the specific gravity of a sample of dense peat from Norway increased in six days from 0·90 to 1·23; while that of a sample of prepared peat increased in the same time from 1·17 to 1·31. The specific gravity of prepared peat is sometimes as high as 1·4; it is not easily broken, but is sufficiently brittle to be powdered under the hammer.

The quantity of ash in air-dried peat may range from 1 to 50 per cent. The best kinds of peat have only 1 to 2 per cent. of ash, but many varieties must be considered unfit for use as fuel on account of the large proportion of ash which they contain.

The following may be taken roughly as the composition of air-dried peat of good quality:[1]—

Carbon	50 to 60	per cent.
Hydrogen	5 to 6	,,
Oxygen	30 to 35	,,
Nitrogen	1 to 2	,,
Ash	5 to 10	,,
Moisture	10 to 20	,,

The calorific power of good air-dried peat varies from 3500 to 5000 calories per kilo (6300 to 9000 Brit. T.U. per pound). Prepared peat has a somewhat higher calorific value, viz. 4000 to 5500 calories per kilo, or 7200 to 10,000 Brit. T.U. per pound.

When heated without free access of air peat can be carbonised, leaving a residue of peat-charcoal, the yield being about one-third of the weight of the air-dried peat. The volatile matter given off during the process contains a great deal of steam, the quantity being somewhat greater than the amount of uncombined moisture in the peat; there is also a considerable quantity of gas containing carbon dioxide, carbon monoxide and methane, which will burn with a luminous flame; and there are condensable tarry vapours which have a very offensive odour. In consequence of the large amount of moisture and other volatile substances (compared with the non-volatile or fixed carbon), peat, like wood, is not suited for use in ordinary gas-producers, when the gas has to be cool and free from tar. When the gas is to be used in furnaces the tar need not be allowed to condense, and it then serves to enrich the gas. Peat contains very little sulphur and would therefore be of great use as fuel in certain metallurgical operations if it were otherwise suitable. For example, in iron-smelting the fuel should contain as little sulphur as possible, in order that the metal may not be contaminated. Peat itself would not give the required heat, and peat-charcoal is too friable to support the weight of ore and fuel above it; but air-dried peat can be used in gas-producers, and the gas made with it can be used for smelting. This system

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[1] "Fuel and Water," Schwackhöfer and Browne, p. 64.

has been adopted in Sweden, and with it a very pure iron is obtained.

Brown Coal or Lignite.—This fuel is intermediate in composition between peat and common coal. It is not found to any extent in the United Kingdom, but there are extensive deposits on the Continent, chiefly in Austria and Germany, and it is much used. Strictly speaking, lignite is a variety of brown coal, but the two terms are often used indiscriminately. The composition of different varieties of brown coal varies within wide limits, some kinds approaching more nearly to peat, while others resemble common coal in their chemical composition, as shown by the following table:—

TABLE XXI.—COMPOSITION OF BROWN COALS.

	Composition per cent. (fuel free from ash and moisture).		
	Carbon.	Hydrogen.	Oxygen and nitrogen.
Peat	59	6·0	33·0
Brown coals—			
Lignite	60	5·5	34·5
Common brown coal	70	5·0	25·0
Pitch coal	75	5·5	19·5
Common coal	82	5·0	13·0

The amount of nitrogen in brown coal is usually less than 1 per cent., and there is generally from 1 to 2 per cent. of sulphur in combination with iron in the ash, but sometimes there is considerably more than this.

In its natural state brown coal usually contains from 30 to 40 per cent. of moisture; before use it is dried by exposure to air, and the proportion of moisture is thus reduced to 10 or 20 per cent. The amount of ash in brown coal should not be greater than 10 per cent., and it may be as low as 2 per cent.; but in some cases the quantity of ash is excessive, reaching as much as 50 per cent.

The calorific power varies from 4000 to 6000 calories per kilo (7200 to 10,800 Brit. T.U. per pound).

On the Continent brown coal is used as a fuel for industrial purposes, and also to some extent for the production of illuminating gas by heating it in retorts. In this process tar and ammoniacal liquor are obtained, but neither these nor the gas itself are as valuable as the gas and products obtained from common coal. Some varieties yield a coke which can be used in the production of iron. Of late years *lignite*, which is the form of brown coal most nearly allied to peat and contains very little bituminous matter, is coming into favour in Germany for the manufacture of producer gas.

Common Coal.—There are many different varieties of coal, and they merge one into another so that no rigid classification according to their chemical composition is possible. For practical purposes they are divided roughly according to their behaviour on heating. Certain kinds of coal give very little smoke or flame, and their volatile matter contains practically no condensable hydrocarbons. These coals are known as anthracite, and as they are of special importance in connection with producer gas they are dealt with later in a separate section. Ordinary coal, on heating, yields considerable quantities of gas and tar, which are the products of decomposition of the bituminous matter in the coal: such coals are said to be semi-bituminous or bituminous, according to the amount of their volatile constituents. Roughly speaking, the amounts of volatile matter in coal (reckoned as dry and free from ash) are as follows :—

Anthracite	4 to 10 per cent.
Semi-bituminous coal	10 to 20 „
Bituminous coal	20 to 40 „

Cannel coal is a variety intermediate in composition between lignite and bituminous coal, and it is specially valued for the production of illuminating gas. The amount of volatile matter in lignites and in cannel coal varies from 40 to 55 per cent.

The behaviour of coal on heating also serves as the basis of the division of bituminous coals into *caking* and *non-caking* varieties. Caking coals are those which on heating fuse or soften. After the volatile matter has been driven off no trace of the original form of the coal is left; the residue of coke has an open cellular structure and is hard and resistant to crushing. Non-caking coals do not fuse or soften when heated; the residue either retains the shape of the original pieces of coal, or else crumbles to pieces and is of little value as a fuel on this account.

Caking and non-caking coals are very similar in chemical composition. Their composition and specific gravity are shown in the following Table :[1]—

TABLE XXII.—COMPARISON OF CAKING AND NON-CAKING COALS.

	Specific gravity.	Composition (per cent.) of coal, dry and free from ash.				
		Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Sulphur.
Caking coals . .	1·25 to 1·35	80 to 90	4·5 to 6	5 to 13	1 to 2·5	0·5 to 2·5
Non-caking coals	1·25 to 1·40	70 to 85	4·5 to 6	10 to 18	1 to 2·0	0·5 to 1·5

The non-caking varieties of bituminous coal contain more volatile matter than the caking coals, and yield less coke when heated in retorts. They are not used for the manufacture of lighting-gas, but are more suitable than caking coals for use in gas-producers. Caking coals soften on heating, and in a gas-producer this leads to the formation of a hollow fire; the gas then passes through the producer without coming thoroughly into contact with the heated fuel, and is of a very inferior quality. For this reason caking coals are seldom used for producer gas, and if they are used special precautions must be taken to break up the fused masses of coal, in order to prevent the fire from becoming hollow.

The proportion of ash in good coal usually varies from 1 to 10 per cent., but it is not an uncommon thing to find samples containing as much as 20 or 30 per cent. of ash. The calorific power varies from 7500 to 8500 calories per kilo (13,500 to 15,300 Brit. T.U. per pound).

Coke.—Coke is the non-volatile residue left when bituminous coal is heated without air for combustion. Large quantities of it are made as a by-product in the manufacture of lighting-gas. The gas-coal is heated in retorts and almost the whole of the volatile matter in it is driven off, the coke left in the retorts

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[1] "Gas Manufacture," Butterfield, p. 8.

being about 60 per cent. of the weight of the coal; so that about 5 tons of "gas-coke" are produced for every million cubic feet of lighting-gas made. A part of this coke is often used at the gasworks for the manufacture of water-gas in gas-producers, this gas being afterwards carburetted and mixed with the ordinary lighting-gas made in retorts. Coke used for making water-gas should contain as little ash as possible, and should be screened free from dust. The best coke from the retorts should be used.

The composition of a good gas-coke is approximately as follows:—

Carbon	89·6 per cent.
Hydrogen	0·4 „
Oxygen and nitrogen	2·0 „
Ash	8·0 „

A coke of this composition would have a calorific power of about 7300 calories per kilo (about 13,000 Brit. T.U. per pound).

Gas-coke, however, varies considerably in its composition, and care should be exercised in choosing a suitable source of supply when the coke is to be used for making producer gas. Generally the coal used in gasworks is selected with a view to its gas-making properties, and if the coal is rich in ash the coke obtained from it will also contain a high proportion of ash. It is obvious that on the average coke must contain more ash than coal, since it contains all the ash but is itself equal to only about 60 per cent. of the total weight of the coal. Thus a coal containing 6 per cent. of ash would yield a coke containing about 10 per cent. Where a part of the coke is to be used in the gasworks for making water-gas it is probable that some attention is paid to this point in selecting the coal used in the retorts, and the gas-coke will not then contain more than 10 per cent. of ash. Gas-coke is often met with, however, containing as much as 15 or 20 per cent. of ash.

Large quantities of coke are also produced in coke ovens, the object in this case being to obtain a coke suitable for iron-smelting and other metallurgical processes. Gas-coke is too light and porous for this purpose, and it is also too impure. A hard dense coke can be obtained if the carbonisation is carried out more gradually, as is the case in coke ovens; and in order to obtain a coke comparatively free from sulphur and ash such as is required by the iron-master the coal used is selected with this object in view, and if the proportion of ash is high the coal is washed to remove the mineral matter (chiefly shale and pyrites) before it is carbonised.

A typical analysis of oven-coke, as it is called, is as follows:[1]—

Carbon	93·15 per cent.
Hydrogen	0·72 ,,
Nitrogen	1·28 ,,
Oxygen	0·90 ,,
Ash	3·95 ,,

The calorific power of this sample would be about 7700 calories per kilo, or 13,900 Brit. T.U. per pound.

Oven-coke is better than gas-coke for use in gas-producers, because it contains less ash and less sulphur; it has a higher calorific power and yields a smaller proportion of dust in handling. Gas-coke is, however, more often used, as it can generally be obtained from a local source and is cheaper than oven-coke.

Anthracite.—Great Britain and the United States have by far the most important output, but there are also anthracite pits in Belgium, France, Germany, Japan, Russia and Spain. Anthracite is said to be found also in South America (Brazil and Chili); and it is believed that there are extensive deposits in China, but they have not yet been opened up. In Great Britain anthracite is found in South Wales, the main field being partly in Glamorganshire, partly in Carmarthenshire, and partly in Brecknockshire, extending from the Neath Valley in the east to Carmarthen Bay in the west, a distance of some 25 miles. There are about forty-four collieries working seams varying in thickness from 6 to 0·5 meters (18 ft. to 18 ins.). The present annual output is about 2½ million tons per annum. The greater part of it is used for burning lime, hop-drying, malting, firing steam-boilers, domestic stoves, etc. Since the introduction of producer gas for engines and heating work the anthracite trade has changed considerably, and in the opinion of

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[1] "Chemistry for Engineers and Manufacturers," Blount and Bloxam, vol. ii. p. 93.

several pit-owners the sale of anthracite for producer gas will eventually be greater than for any other purpose. The shipments abroad from Swansea for producer gas alone are extensive and increasing.

The anthracite and semi-bituminous varieties of coal are often found near together, and merge into one another. Anthracite is hard and dense, and has a conchoidal fracture; it has been defined as "the ultimate product of the conversion of vegetable matter into coal." Its average composition is given in Table XIX., but its quality varies considerably because so many veins are worked, each having its own peculiarity. There are also several sizes produced at the principal pits, to suit various requirements; and these sizes are sold at different prices. It is, therefore, important for the user of a gas-plant to know the size and quality of anthracite he should buy; and, apart from the question of price, he will find that the best size for his producer will chiefly depend on the design and the mode of working the latter.

When Mr. Dowson first introduced his gas-plant little attention was given in this country to the sizing of anthracite, except for close stoves of the American type. These required "nuts," which would pass through screens having round holes from 38 to 50 mm. (1½ in. to 2 ins.) diameter, and as they were exported chiefly to France and Germany they were usually called French and German nuts. He began by using these in his gas-producers, and for plants of large size he used "cobbles," which are larger than nuts. In the production of these sizes a considerable proportion of small coal was formed, and for this there was little or no sale; as the use of producer gas extended, this comparatively unsaleable product became a serious consideration, and tended to raise the price of the nuts. Mr. Dowson, therefore, modified his producer so that a smaller size of anthracite called "peas" could be used, and this reduced the price of the fuel for the producer by five to six shillings a ton. The use of producer gas has greatly increased since then, and there are now numerous makers of gas-plants. The quantity of small anthracite required to keep pace with the demand is at times greater than that produced in the sizing of "nuts." This has led the principal collieries to give closer attention to the sizing of the coal, but they often find it difficult to make each size in the proportion required for a varying demand. When the coal reaches the pit mouth so much of the "large" as is not required of that size is broken and passed over a series of screens with different-sized openings, and usually the following sizes of anthracite are produced:—

Large—will not pass through a 5-in. (127-mm.) opening.

Cobbles—have passed through 5 ins., but will not pass through $2\frac{1}{2}$ to 3 ins. (63 to 76 mm.) square.

Nuts (French)—have passed through $2\frac{1}{8}$ ins. (54 mm.) diameter, but will not pass through $1\frac{3}{4}$ in. (44 mm.) diameter.

Nuts (German)—have passed through $1\frac{3}{4}$ in. (44 mm.) diameter, but will not pass through $\frac{3}{4}$ in. (19 mm.) or 1 in. (25 mm.) square.

Peas or Beans—have passed through $\frac{3}{4}$ in. (19 mm.) or 1 in. (25 mm.) square, but will not pass through $\frac{3}{8}$ in. (9 mm.) square.

Duff (residue)—have passed through $\frac{3}{8}$ in. square.

The demand for the various sizes varies considerably at different seasons and at different times; the crushers are therefore made adjustable, so that when required they can be opened or closed to produce a higher or lower percentage of "large." Other manipulations are resorted to, but the difficulty remains of avoiding waste in producing the sizes required for a varying demand. Even in the best-managed collieries the actual waste in coal too small for use is about 10 per cent. of the total output, sometimes more, and this loss is covered by a higher price being charged to the consumer.

In a gas-producer it is important to make as little clinker as possible, and for this reason it is usual to specify anthracite which has a low percentage of ash. The best anthracites contain about 2 to 3 per cent. of ash, but many contain from 5 to 7 per cent., and all these can be used in a suitable producer. If there is more than 7 per cent. of ash special care should be taken to avoid trouble with clinker. The mere percentage of ash is, however, not a precise indication of the suitability of the anthracite; it is only an approximation to it. It is important to take into account the fusibility of the ash; this depends upon its composition, especially as to the amounts of basic substances present (oxides of iron, calcium, aluminium, etc.) in relation to the amount of silica.

Speaking generally, these oxides will combine under the influence of a high temperature with the silica in the ash or in the refractory lining of the producer. The compounds thus formed (silicates) will be more or less fusible according to their composition; the silicate of aluminium fuses only at a very high temperature, while that of iron is fused with comparative ease.

If the incombustible residue remains in the condition of ash, or if it is partially fused, forming loose pieces of clinker, it can be easily removed from the producer; but there is always a tendency for the basic constituents of the residue to combine with the siliceous matter and to form fusible silicates which adhere tenaciously to the lining, and in time adherent slag or clinker will block the fire. Its removal is attended with difficulty, and the best practical method of dealing with the trouble, when circumstances make it desirable to employ a fuel of this character, is to reduce the temperature in the lower part of the fire by passing through it an excess of steam.

Where the producer is worked with a jet of steam it is easy to give an excess of the latter, but in a producer of the suction type it is not so easy. It is not an uncommon defect in a suction gas producer that there is not enough steam to give a sufficient percentage of hydrogen in the gas. This favours an exceedingly high temperature in the fire, and the formation of a troublesome amount of clinker. There have been many cases where complaints have been made of the quality of the anthracite, when in reality it was good but there was too little steam. As a practical outcome of this, the colliery managers now know that the gas-plants of certain makers cause more complaints to be made about the anthracite than the plants of other makers; and there is no doubt that it would be greatly to the interest of the makers and users of gas-plants, as well as of the collieries, if the designers of gas-producers gave closer attention to the right use of the fuel on which the working depends.

Another question of importance is the proportion of coal-dust which may be present with the large pieces, and indirectly this also bears on the question of clinker. In the majority of producers of moderate size there is a grate to support the fuel in which the open spaces between the bars allow air to come in contact with the fuel over an extensive surface. If much dust is used it falls through the bars, and if the bars are put close enough together to prevent this the air-spaces are considerably reduced. There are various ways of getting over this difficulty, but a more serious trouble is that if there is much dust with the coal it chokes the fire, and the currents of steam and air do not pass through it readily and evenly. The result is bad gas. It is also a fact that when there is much dust with the coal there is generally a larger proportion of impurities. *Primâ facie* one might suppose that if a large lump of coal were broken into pieces of any size there would be the same proportion of impurities in a given weight of any size, including the coal-dust. But actually the case is not quite so simple; not all the coal is in large lumps when it reaches the pit's mouth, and there is necessarily a mixture of various sizes, including some roofing and other impurities. The "large" which is removed for sale usually represents something like a fourth to a third of the total, so that a larger proportion of impurities is left in the remaining three-fourths or two-thirds. Then, as the coal is broken and passes over screens of various sizes, the cleanest is "creamed off," and the small pieces remaining contain a larger proportion of impurities. This is the case if much dust is allowed to remain with the small pieces called "peas," and at several pits it has led to the washing of the "peas" used for gas-producers. This process adds about one shilling per ton to the cost.

The following analyses are instructive, as they show the difference in composition of good qualities of anthracite in the "large" size, and of "peas" produced from the same class of coal:—

TABLE XXIII.—COMPOSITION OF ANTHRACITE (LARGE AND PEAS).

	Large size.			Peas.		
	Carbon.	Volatile matter.	Ash.	Carbon.	Volatile matter.	Ash.
No. 1	92·73	6·06	0·76	90·0*	5·1	2·5
" 2	92·53	5·57	1·15	90·2*	5·6	4·2
" 3	91·95	5·67	1·55	89·4*	5·5	3·9
" 4	91·37	6·06	1·97	90·1	5·5	4·4

* These peas were washed.

These analyses show that in the "peas" there was an average decrease of 2·22 per cent. in the carbon, and an average increase of 2·39 per cent. in the ash. These samples are better than the average sold, and frequently the percentage of ash in "peas" is as high as 7 per cent.—sometimes higher. We have, however, already explained that the composition of the ash, especially the percentage of iron, is even more important for gas-producer work than the mere percentage of ash in the coal. It is for this reason that some of the lower grades of anthracite are suitable, for although they contain a high percentage of ash, the latter contains little or no iron, and little clinker is formed. From the buyer's point of view it would clearly be better to be without dust, if he has to pay as much for it as for "peas" or "nuts," as the carriage per ton will be the same whatever the quality may be. Some makers of gas-plants even advise their clients to buy "nuts," although they cost much more than "peas;" but if the producer is rightly designed there should be no more waste with "peas" than with "nuts," and the time will probably come when means will be found to use up all the small produced, including a large proportion of the vast heaps of "duff" and waste now accumulating at the principal collieries. It is easy for the maker of a gas-plant to recommend a costly high grade of anthracite; but, looking broadly at the future, it will benefit all concerned and help to develop the use of gas-power if means are devised for using the lower grades of anthracite, because the output is large and the price is lower than that of the best picked coal now generally used for gas-making.

When gas made from anthracite was first introduced on the Continent "nuts," such as were burnt in American stoves, were used in the gas-producer. Later "peas" were adopted, but the voyage, and especially the trans-shipments, caused an appreciable loss from dust. In France, Germany, and Italy this has led to the importation of anthracite from South Wales in large sizes, and to its being broken and sized at depôts after its arrival. This is especially desirable with the softer kinds of anthracite, which are more friable: we have known of a shipment of "peas" containing over 30 per cent. of dust on arrival.

Another matter of importance is the presence of volatile matter in anthracite, because it often gives rise to tarry and other troublesome products in the gas. This varies considerably in different qualities of coal, but in Welsh anthracite it varies from about 4 to 10 per cent. Recent investigations have shown that many anthracites, probably all, yield more or less tarry matter when distilled in the absence of air. In a gas-producer air comes in contact with the fuel in the lower part of the fire; but there should be no free oxygen in the upper part of the producer, and a large proportion of the fuel in this upper part is sufficiently heated to distil off any volatile matter without contact with air. The nature of the volatile matter is, however, of greater importance than its amount: we have had occasion to deal with an anthracite containing only 6·2 per cent. of volatile matter, which nevertheless made the producer gas decidedly tarry. On heating a sample of this coal (out of contact with air), it gave off small quantities of tarry vapour such as would come from a bituminous fuel. On the other hand, we have used anthracite containing as much as 6 or 10 per cent. of volatile matter which did not make the gas tarry. It is probable that in all producers worked with anthracite there is a slight yield of tarry matter; but its extent will be influenced by the nature of the volatile matter in the anthracite and the temperature to which it is subjected in the upper part of the producer.

We have spoken chiefly of anthracite from South Wales because this is the chief source of supply in Europe, but we are pleased to add that there is also a fairly good supply in Scotland. The anthracite there is usually sold in two sizes, *singles* and *doubles.* The latter are used chiefly for stoves, and the former for gas-producers. There is a higher percentage of ash in Scotch anthracite than in the best kinds from South Wales; but on the other hand, the selling price of the former is only about half that of the latter, owing to the wages and working expenses at the collieries being much higher in South Wales than in Scotland. At trials made in 1905 on behalf of the Highland Society (at their Agricultural Show) it was proved that with a gas-engine and suction plant fired with Scotch anthracite costing only nine shillings a ton delivered in Glasgow the actual consumption was under 1 lb. per B.H.P.-hour, even when working on such a small scale as 10 to 20 B.H.P. Quite recently some anthracite pits have been opened in Ireland, and the quality of the coal is promising.

In Belgium and France the anthracite usually contains more ash and more volatile matter than the anthracite from South Wales; in many cases it should properly be classed as semi-bituminous coal. In France the best anthracite is obtained in the Departments of the Nord and of the Pas de Calais; in the former the Compagnie des Mines d'Anzin have very extensive workings, and to meet the varying requirements of their customers they have given close attention to the sizing of their anthracite. They have now adopted the following elaborate classification, the figures given being the diameters of round holes in the screens through which the coal is passed:—

Schlamms—residues from the washers.
Poussiers—2, 4, 8, and 10 mm.
Greneux—2 to 5, 2 to 7, 5 to 7, 4 to 8 mm.
Grains—5 to 13, 7 to 13 mm.
Grenus—10 to 20, 13 to 20, 20 to 30 mm.
Braisettes—30 to 55, 45 to 55, 55 to 80 mm.
Petite gailletterie—70 to 120, 80 to 120 mm.
Grosse gailletterie—pieces above 120 mm.
Gros—size prepared by hand.

Besides these there are several other grades, depending on whether the coal is or is not riddled and washed free from dust. The average calorific power of this anthracite is said to be from 7500 to 7700 calories per kilo, or 13,500 to 13,860 Brit. T.U. per pound.

CHAPTER XIII

ANALYSIS OF FUEL AND OF PRODUCER GAS

Analysis of Fuel.—The chemical analysis of fuel consists either of the ultimate analysis, *i.e.* the determination of the proportions of carbon, hydrogen (chemically combined), oxygen, nitrogen, sulphur, ash and moisture; or of the proximate analysis, which consists of the determination of fixed carbon, volatile matter, ash and moisture.

For industrial purposes the ultimate chemical analysis is seldom required. The character of a fuel and its suitability for a particular purpose can be judged from the results of the proximate analysis, and when a fuel is to be used in gas producers it is usually sufficient to know the results of the proximate analysis, together with the percentage of sulphur in the fuel and the calorific power. Methods for the ultimate analysis of fuel are described in text-books on quantitative analysis and need not be repeated here. The methods described below for the proximate analysis of fuel are those recommended by a Committee of the American Chemical Society.[1]

Sampling.—In making an analysis in the laboratory only a very small quantity of the fuel is actually tested, and it is of the utmost importance that the sampling and subsequent preparation of the fuel should be carried out in such a way that the small quantity which is tested truly represents the average of the whole bulk. The method which is recommended in testing a consignment of coal is as follows:—

Shovelfuls of coal are taken at regular intervals during the unloading of the truck. The coal thus taken is placed on a close floor and is broken till there are no pieces larger than about

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[1] "Report of the Committee on Coal Analysis," *Journal of the American Chemical Society*, 1899, vol. xxi. pp. 1116-1132.

75 mm. or 3 in. cube. It is then well mixed and divided roughly into four equal parts; opposite quarters are rejected and the remaining half of the coal is broken to a smaller size. This process is repeated until the sample is reduced to about 1 kilo. in weight and consists of pieces about 5 mm. cube. It is then sealed up in an air-tight jar and kept for analysis. To avoid alteration in the percentage of moisture in the coal these operations should be carried out as quickly as possible.

To prepare the sample for analysis the process of quartering is continued until a sample weighing about 100 grams or ¼ lb. is obtained, and this is ground as quickly as possible to a coarse powder in a suitable mill. An ordinary coffee-mill answers well for this purpose. A portion of this coarsely ground sample is at once transferred to a tightly stoppered bottle and kept for the determination of moisture.

About 15 grams or ½ oz. of the remainder of the powdered sample is ground moderately fine in an iron or porcelain mortar, and is kept in a stoppered bottle for use in the other determinations.

Moisture.—The percentage of moisture is determined by drying one gram of the coal in an open porcelain crucible, either by heating it for one hour in an oven kept at 104 to 107° C., or by exposing it for twenty-four hours over concentrated sulphuric acid in a vacuum desiccator. The latter method is the more accurate; the former gives a slightly lower result, but is sufficiently accurate in view of the fact that some slight alteration in the percentage of moisture probably takes place during sampling.

The percentage of moisture should be determined in both the coarsely ground and the finely powdered samples. Generally some moisture will have been lost during the process of grinding in the mortar, and all the results obtained in which the finely powdered sample has been used must therefore be corrected. Suppose the results of an analysis are as follows:—

	Coarsely ground.	Finely powdered.
Moisture	3·26 per cent.	1·30 per cent.
Ash	—	12·55 „

The percentage of moisture in the coal is 3·26; the percentage of ash was determined in the finely powdered sample which contains only 1·30 per cent. of moisture, and the necessary correction is easily made:—

100 grams of the coarsely ground sample with the true percentage of moisture contain (100 − 3·26) grams of dry coal; 100 grams of the finely powdered sample contain (100 − 1·30) grams of dry coal of which 12·55 grams are ash.

The percentage of ash in the coarsely ground coal is the weight of ash in (100 − 3·26) grams of dry coal,

$$\text{or } 12{\cdot}55 \times \frac{100 - 3{\cdot}26}{100 - 1{\cdot}30} = 12{\cdot}30 \text{ per cent.}$$

Thus the percentages of ash or of volatile matter found by analysis of the finely powdered sample must be multiplied by a factor which is equal to:—

$$\frac{100 - \text{percentage of moisture in coarsely ground sample}}{100 - \text{percentage of moisture in finely powdered sample}}$$

Volatile Matter, other than Moisture (*Volatile Combustible Matter*).—This is determined by heating the coal under certain specified conditions. The residue which is left is not entirely free from hydrogen, and by prolonged heating at very high temperatures more volatile matter can be expelled. The complete expulsion of the hydrogen can only be attained at temperatures which are too high to be practically used in the analysis. Consequently it is necessary to specify certain arbitrary conditions for the heating, which will give comparative results with different samples of coal. The following is the procedure recommended by the Committee:—

One gram of the finely powdered coal is placed in a platinum crucible weighing 20 to 30 grams, and having a tightly fitting cover. The crucible is heated over the full flame of a Bunsen burner for seven minutes. The crucible should be supported on a platinum triangle with the bottom 6 to 8 cms. above the top of the burner. The flame should be 20 cms. high when the crucible is removed, and the determination should be made in a place free from draughts. The upper surface of the cover should remain clear, but the under surface should remain covered with carbon.

The loss in weight gives the percentage of volatile matter and moisture, and the percentage of moisture in the powdered sample must be deducted from this. There is no mechanical loss of coal during the heating, even with samples rich in volatile matter.

Ash.—The portion of powdered coal which has been used for the determination of moisture is heated in the open crucible until all carbon is burnt away. The weight of the residue in the crucible gives the quantity of ash left by the combustion of the powdered sample.

Fixed Carbon.—This is calculated as the difference between 100 and the sum of the percentages of moisture, volatile matter and ash. The sulphur in the fuel is included partly in the volatile matter and partly in the ash, and is therefore not taken into account in calculating the percentage of fixed carbon by difference.

When sulphur is present as pyrites (iron sulphide, FeS_2) the amount of ash left on burning the coal is less than the amount of mineral matter in the coal, because the sulphur in the pyrites burns away and is replaced by three-eighths of its weight of oxygen, the pyrites being converted to iron oxide. The value of the fixed carbon is therefore not given accurately as the difference required to make up 100 per cent. For ordinary purposes the fixed carbon is calculated as described above, but if the results of the proximate analysis are used for calculating the calorific power it is better to take the corrected value for the fixed carbon. This is less than the amount required to make up the 100 per cent. by five-eighths of the weight of sulphur present as pyrites. For this purpose the total sulphur in the fuel is determined as described below, and it is sufficiently accurate to assume that all of this is in combination as pyrites.

Sulphur.—The total percentage of sulphur in the fuel is determined by Eschka's method as follows :—1 gram of the finely powdered coal is thoroughly mixed with 1 gram of light magnesium oxide and 0·5 gram of dry sodium carbonate in a thin platinum dish of about 75 to 100 c.c. capacity. The dish is gently heated over a spirit lamp, the heat being raised very gradually until the carbon is burned away. (Gas must not be used for the heating on account of the sulphur which it contains.) The sulphur in the coal is thus oxidised and is fixed by the sodium carbonate and magnesium oxide. The mass is transferred to a beaker and the dish is rinsed with about 50 c.c. of water; 15 c.c. of saturated bromine water are added and the liquid is boiled for five minutes, allowed to settle, and then decanted through a filter. The residue is twice extracted with boiling water and then washed on the filter. The filtrate now contains all the sulphur in the form of sulphate; it is acidified with hydrochloric acid and boiled till free from bromine. The sulphate is then estimated in the usual way as barium sulphate.

When the coal tested contains much pyrites or calcium sulphate, the residue of magnesium oxide should be dissolved in hydrochloric acid and tested for the presence of sulphate.

Calorific Power.—The methods for determining the calorific power of coals are described in the next chapter.

Analysis of Producer Gas.—The chemical analysis of producer gas consists in the determination of the proportions by volume of carbon dioxide, oxygen, carbon monoxide, hydrogen, methane and in certain cases ethylene (C_2H_4). The difference required to make up 100 per cent. is assumed to be nitrogen. The weight of sulphur in a given volume of the gas is also sometimes determined. In the volumetric analysis the gases containing sulphur are not separately determined, and are included with the carbon dioxide. Their volume is, however, very small.

There are many forms of apparatus which can be used for this analysis, and for some of the constituent gases alternative methods of analysis are available. For full detailed information on the whole subject, the reader is referred to text-books on Gas Analysis. We will confine ourselves here to the description of a method of analysis which has been found very convenient in practice.

The method of collecting the sample for analysis depends upon the object of the test. If it be required to determine the composition of the gas at any particular time the sample may be transferred direct from the gas main to the sampling tube. The latter may conveniently be of the form shown in Fig. 65. The bulb **A** has a capacity of about 120 c.c.; the lower end terminates in a tube 7 mm. in diameter; a similar tube at the other end of the bulb terminates in a short tube **B** of capillary bore. A short piece of rubber tubing with a pinch-cock is connected to each end of the sampling tube. The capillary end of the tube is connected to the gas supply and the gas is blown through the bulb for a sufficient time to remove all the air; the pinch-cocks are tightly closed and the sample is at once taken to the laboratory and analysed. The sample may also be drawn into the tube by displacement of water. For this purpose the tube is completely filled with water which has been saturated with the gas; the capillary end **B** is connected to the gas supply and the pinch-cock opened. By opening the pinch-cock on the lower end the water is allowed to run out, and its place is taken by gas from the main. A small quantity of water is left in the lower end of the tube; after the cocks have been closed and the tube disconnected from the gas main it is inverted in order to allow a little of the water to enter the capillary. On returning the tube to the vertical position the gas is confined between two short columns of saturated water, so that it can be kept for a short time without undergoing any alteration in composition by diffusion through the rubber. If the sample cannot be analysed soon after it is collected, the ends of the rubber tubing should be closed by short pieces of glass rod, and the whole of the rubber covered with paraffin wax. The amount of water which has been left in the tube should be as small as is consistent with avoiding contact of the gas with the rubber. With these precautions the sample may be stored for one or two days if necessary.

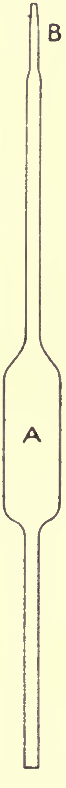

Fig. 65.—Gas sampling tube.

The object of analysing producer gas is more often to ascertain the average composition during a period of one or two hours, and for this purpose the above method of sampling is obviously unsuitable. The apparatus shown in Fig. 66 is very convenient for regular sampling, when it can be set up permanently in a convenient spot. The sample is collected in the aspirator **E**, which has a capacity of 5 liters. A capillary tube **K**, provided with a cock **D**, connects the aspirator with the gas main **J**. The aspirator is filled with saturated water from the bottle **G** by means of the glass tube **H** leading to the bottom of the aspirator; the air or previous sample of gas which may have been in the aspirator escapes through the cock **B**. The aspirator having been completely filled with water, cocks **A** and **B** are closed and **D** is opened. Water is now allowed to drip at the cock **C**, the rate being adjusted so that the aspirator will be rather more than half emptied at the end of the period during which the sample is to be collected. The sample of gas thus slowly collects above the water in the aspirator, and as the producer gas is continually passing the point **F** where it is drawn into the capillary tube, the sample obtained represents an average of the whole of the gas passing through the main. The water should escape from the aspirator approximately at a constant rate, and to secure this the cock **C** should be well below the bottom of the aspirator, so that the alteration in the head of water will make very little difference to the rate of flow. In regular sampling from the same installation the same saturated water is continually in use in the aspirator, and as the gas will not vary much in composition its exposure over a large water surface in the aspirator will not cause any alteration in

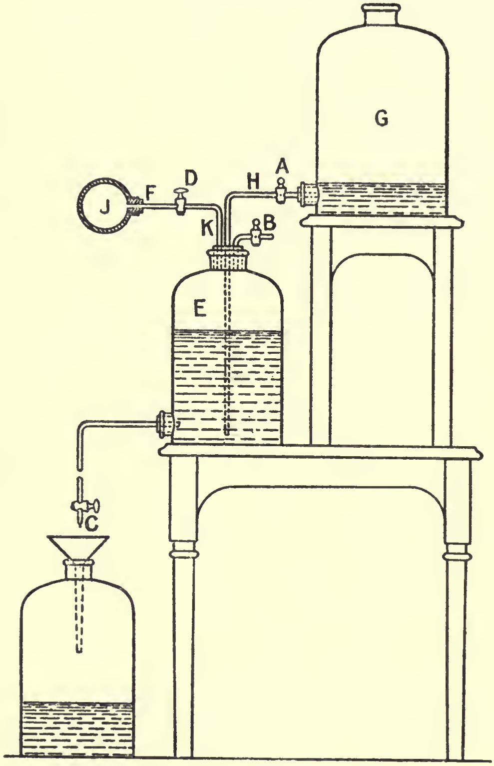

Fig. 66.—Gas sampling apparatus.

composition. In other cases, where the water cannot be regarded as saturated with the gas or where the composition of the gas to be tested differs much at different times, the water in the aspirator may be covered with a layer of petroleum (boiling point 195° to 200° C), which does not absorb any of the constituents of the gas, or a solution of brine may be used instead of water.

In order to transfer the sample to the laboratory for analysis, the water which has run out at **C** is poured into the bottle **G**, and the gas sampling tube (Fig. 65) filled with saturated water, is connected at its capillary end to the capillary tube **B**. The cocks **A** and **B** are opened (**C** and **D** being now closed), and on releasing the pinch-cocks on the sampling tube the water in **G** passes into the aspirator, forcing the gas through **B** into the sampling tube. Several sampling tubes may be filled in this way, the remainder of the gas in the aspirator being allowed to escape at **B**.

The apparatus used for the analysis of the gas is that devised by Macfarlane and Caldwell,[1] with some slight modifications. The apparatus is shown in Fig. 67. The measuring tube **A** is graduated up to 50 c.c. and forms one limb of a **U** tube which is connected by rubber tubing to the mercury reservoir **B**. The latter is raised or lowered as required by shifting the balance weight **C**. The cock between the **U** tube and the mercury reservoir is closed while the latter is moved; and by opening this cock the mercury can be allowed to flow to or from the **U** tube as required. The **U** tube is surrounded by water in a cylindrical jacket, so that the gas is always brought to the temperature of the water in the jacket before it is measured.

The upper end of the graduated tube **A** terminates in a capillary tube and a special cock **D**. The gas pipette **E** slides in a groove on the stand **F**, and is connected by rubber tubing to the cock **D**; it can be firmly clamped in its place by means of the screw **G**. The cock can be turned so as to bring the pipette into communication either with the measuring tube or the flask **H**. The stand **F** which carries both the **U** tube and the gas pipette is pivotted at **K** and can be rocked to and fro, or it can be clamped tightly in position by the screw **L**. A cock **M** is provided for drawing off the mercury when required.

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[1] *Journal of the West of Scotland Iron and Steel Institute*, 1892, No. 2, vol. i.

The analysis of the gas consists of the following operations :—

1. Absorption of carbon dioxide by caustic potash.
2. Absorption of oxygen by alkaline pyrogallol.

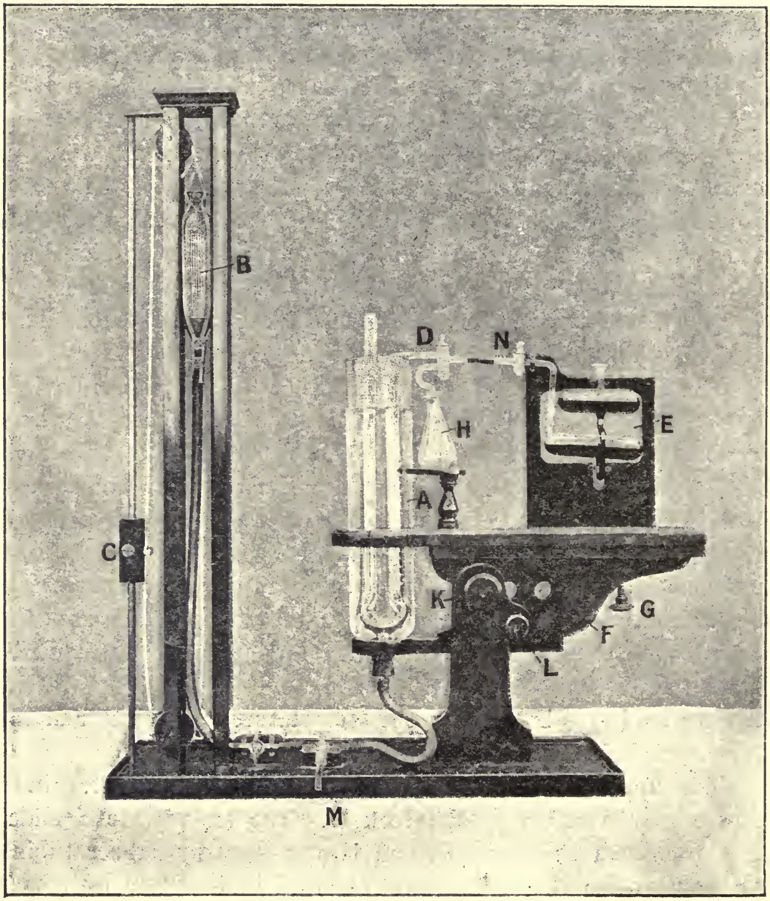

Fig. 67.—Apparatus for gas analysis.

3. Absorption of carbon monoxide by an acid solution of cuprous chloride.
4. Explosion of a portion of the residue mixed with hydrogen and air.
5. Absorption of carbon dioxide formed from the methane in the gas during the explosion.

The analysis requires the use of four gas pipettes similar to the one shown in the figure, viz. one each for caustic potash and alkaline pyrogallol, and two for cuprous chloride; also a pipette for supplying hydrogen, and an explosion pipette. The two latter are of the ordinary Hempel form, but with the capillary tube bent horizontally to suit the cock **D**; each pipette has a cock at **N** and is mounted on a suitable stand. The explosion can be made in the measuring tube itself, but it is better to use a separate explosion pipette, as a larger volume of gas can then be taken.

The measuring tube **A** contains about 1 c.c. of saturated water, acidified with sulphuric acid, above the mercury. This can be changed after each analysis, and in this way the mercury is not soiled by contact with the various reagents, and there is always a good meniscus at the upper surface of the water.

In making an analysis the mercury is first of all allowed to rise in the **U** tube until the capillary tube and cock are filled with water. The capillary end of the gas sampling tube is connected to the cock, and its lower end opened under saturated water in a basin. The mercury reservoir is lowered and the stop-cocks are turned so that mercury runs from the **U** tube into the reservoir, and the gas is thus drawn from the sampling tube into the measuring tube **A**. Nearly 50 c.c. should be taken for the analysis. Before the volume of gas taken is measured, the pressure should be adjusted to atmospheric by raising the mercury reservoir and allowing mercury to flow into the **U** tube until it stands slightly higher in the open limb than in the measuring tube. The stop-cock **D** is slightly opened and the motion of the thread of water in it indicates whether the pressure of the gas is above or below that of the atmosphere. With a little practice the adjustment of the pressure is generally exact at the first trial. Three minutes should elapse between the filling of the measuring tube and the measurement of the volume, in order that the water in the measuring tube may drain down the sides.

The next operation is the determination of the carbon dioxide. The pipette containing caustic potash is placed on the stand and connected to the stop-cock **D**, which is turned so as to connect the pipette with the flask **H**. By gently blowing with the mouth through a rubber tube held in the neck of the pipette a few drops of the liquid are forced out into the flask so that the capillary tube connecting the pipette with the measuring tube is completely filled with the reagent. The mercury reservoir is now raised and the stop-cocks are turned so that the gas is forced out of the measuring tube into the pipette. The water in the measuring tube should be allowed to fill the whole length of the capillary as far as the bulb of the pipette. The stand **F** is now rocked to and fro so that the gas is brought thoroughly into contact with the reagent, and absorption is complete in a few seconds. Before transferring the gas back to the measuring tube a little of the water is allowed to run into the pipette from the measuring tube. This washes the capillary tube and prevents the passing of drops of the reagent into the measuring tube. The gas is transferred to the measuring tube, the pressure adjusted and the volume measured with the precautions described above. The decrease in volume is the number of cubic centimeters of carbon dioxide absorbed. The stop-cock is then cleaned by blowing water through it into the flask by means of the wash-bottle.

The manipulation is the same with the other pipettes, and it is only necessary to refer to the special points in each case.

Absorption of Oxygen.—The gas should be in contact with the reagent for three minutes and the stand should be rocked during the whole of this time.

Absorption of Carbon Monoxide.—The gas is agitated with the acid solution of cuprous chloride for three minutes in the pipette. It is then brought back into the measuring tube, a second pipette containing fresh cuprous chloride (which has not been used for the first absorption of carbon monoxide in any analysis) is put on the stand, and the gas is passed into this and shaken for a further period of three minutes. Before its volume is measured the gas is passed into the caustic potash pipette, to absorb the vapours of hydrochloric acid evolved in the cuprous chloride pipettes.

Determination of Hydrogen and Methane.—With ordinary producer gas there will generally be left about 30 to 35 c.c. of gas after the absorption of carbon dioxide, oxygen and carbon monoxide. Part of this must be allowed to escape, and only 15 or 16 c.c. should be used for the determination of hydrogen and methane. About 5 or 6 c.c. of hydrogen are added from the hydrogen pipette, and the volume of hydrogen added is measured. Air is then drawn into the measuring tube until the total volume is nearly 50 c.c. After the volume has again been measured the mixture is transferred to the explosion pipette and exploded. It is then measured in the measuring tube and the contraction is noted. The volume of carbon dioxide formed by the explosion is determined by absorption in caustic potash, and is equal to the volume of methane which was present in the gas taken for this determination. The contraction due to the combustion of the methane is twice the volume of methane. The remainder of the contraction is due to the combustion of the hydrogen, and the total volume of hydrogen in the mixture is two-thirds of this contraction. The volume of hydrogen which was added is deducted, and the remainder of the hydrogen is that which was present in the gas used for the test.

The following example will make clear the method of calculation :—

Volume of gas taken for the analysis	49·2	c.c.
Volume after absorption of carbon dioxide	46·55	„
Volume after absorption of oxygen	46·45	„
Volume after absorption of carbon monoxide	34·5	„
Volume of residual gas taken for determination of hydrogen and methane	15·05	„
Volume after adding hydrogen	20·0	„
Volume after adding air	48·55	„
Volume after explosion	35·7	„
Volume after absorption of carbon dioxide	35·5	„

We then have—

$$\textit{Carbon dioxide} = \frac{49{\cdot}2 - 46{\cdot}55}{49{\cdot}2} \times 100 = 5{\cdot}4 \text{ per cent.}$$

$$\textit{Oxygen} = \frac{46{\cdot}55 - 46{\cdot}45}{49{\cdot}2} \times 100 = 0{\cdot}2 \quad ,,$$

$$\textit{Carbon monoxide} = \frac{46{\cdot}45 - 34{\cdot}5}{49{\cdot}2} \times 100 = 24{\cdot}3 \quad ,,$$

Methane.—15·05 c.c. of the residual gas contained $35{\cdot}7 - 35{\cdot}5 = 0{\cdot}2$ c.c. of methane. But 15·05 c.c. of the residual gas correspond to $15{\cdot}05 \times \frac{49{\cdot}2}{34{\cdot}5}$ c.c. of the original sample, and the percentage of methane is $\frac{0{\cdot}2 \times 34{\cdot}5}{15{\cdot}05 \times 49{\cdot}2} \times 100 = 0{\cdot}9$ per cent.

Hydrogen.—The contraction on explosion was 48·55 − 35·7 = 12·85 c.c.
Contraction due to combustion of methane = 2 × 0·2 = 0·4 „
Therefore, contraction due to combustion of hydrogen = 12·45 „
Total volume of hydrogen present = $\frac{2}{3}$ × 12·45 = 8·3 „
Volume of hydrogen added was 20·0 − 15·05 = 4·95 „

Therefore, volume of hydrogen in 15·05 c.c. of residual gas was 8·3 − 4·95 or 3·35 c.c., and percentage of hydrogen in the original sample

$$= 3{\cdot}35 \times \frac{34{\cdot}5}{15{\cdot}05 \times 49{\cdot}2} \times 100 = 15{\cdot}6.$$

The composition of the gas by volume is therefore:—

Carbon dioxide	5·4	per cent.
Oxygen	0·2	„
Carbon monoxide	24·3	„
Methane	0·9	„
Hydrogen	15·6	„
Nitrogen	53·6	„ (by difference).

No correction for temperature and pressure is needed, because all volumes were measured at the same temperature and pressure, and the proportion of the different constituents is the same at 0° C. and 760 mm. as at any other temperature and pressure.

Ethylene.—The percentage of ethylene is sometimes determined in the gas made from bituminous coal, but it seldom amounts to more than 0·2 per cent. The ethylene is absorbed either by bromine water or by fuming sulphuric acid in a pipette similar to that used for caustic potash. In either case the gas must be passed into the potash pipette after the ethylene has been absorbed, to free it from the vapours either of bromine or of the fuming acid. The determination of ethylene is made immediately after the determination of carbon dioxide.

Sulphur in Gas.—A considerable volume of the gas (say 50 liters) is burnt, and all the sulphur in the gas is thus converted to sulphurous and sulphuric acids. The products of combustion are passed through some reagent which will oxidise the sulphurous acid to sulphuric acid, and the quantity of sulphuric acid formed is determined by precipitation as barium sulphate in the usual way. There are several well-known forms of apparatus for this determination, suitable for different modifications of the method. In Drehschmidt's method, for example, the products of combustion are passed through a solution of potassium carbonate containing bromine as the oxidising agent. Detailed information is given in standard works on analysis.

CHAPTER XIV

CALORIFIC POWER OF SOLID AND GASEOUS FUELS

In order to judge of the efficiency of a gas-producer it is necessary to know not only the quantities of fuel used and gas obtained, but also the amounts of heat which can be obtained by the combustion of each, *i.e.* their calorific powers. The most efficient producer is that in which the total heat which can be obtained by the combustion of the gas bears the highest ratio to the total heat that could have been obtained by the complete combustion of the solid fuel.

When gas is used for the production of power the results of tests are frequently stated in terms of the fuel consumption, *e.g.* 450 grams, or 1 lb. per B.H.P.-hour; but as the calorific power of different samples of coal may vary from, say, 7500 to 8500 calories per kilo (13,500 to 15,300 Brit. T.U. per pound) it is evident that the calorific power of the fuel should be stated as well as the consumption. For example, a producer-gas installation which would give a fuel consumption of 410 grams (0·90 lb.) per B.H.P.-hour with fuel having a calorific power of 7500 calories per kilo (13,500 Brit. T.U. per pound) would show a consumption of only 362 grams (0·80 lb.) per B.H.P.-hour when using a high-grade fuel, the calorific power of which was 8500 calories per kilo (15,300 Brit. T.U. per pound). The total amount of heat supplied to the producer by the combustion of the fuel is the same in each case, but the higher fuel consumption is really the better result of the two, as it means that the efficiency of the producer is the same, although the fuel used was of an inferior and cheaper kind. This example is by no means an exaggerated one, and it indicates that a knowledge of the calorific power of the fuel is important from the point of view of the owner of the plant.

If two samples of coal have different calorific powers, but are otherwise equally well suited for use in the producer, it may sometimes be cheaper to pay a higher price for that coal which has the higher calorific power. In such a case the true basis of comparison is not the price per ton, but the price for equal numbers of heat units.

The value of producer gas, whether used in a gas-engine or for heating or furnace work, depends primarily upon the quantity of heat given out during its combustion, or in other words upon its calorific power.

For engine work it is not essential that the calorific power of the gas should be high. The same quantity of heat can be supplied to the engine by using a larger volume of a weaker gas or a smaller volume of a stronger gas, and gas-engines can be made suitable for using gases differing as widely as ordinary lighting gas and blast-furnace gas, which have calorific powers of about 6000 and 800 calories per cubic meter respectively, or say 650 and 90 Brit. T.U. per cubic foot. The power which can be developed per stroke in an engine cylinder of given dimensions depends chiefly upon the quantity of heat in the mixture of gas and air which is supplied to it; and as the richer gases require more air for their combustion than the weaker ones the power obtained in the same engine is not very much greater with a rich gas than with a poor gas. For example, a semi-water-gas as usually made for engine work gives only about 20 per cent. less maximum power than lighting gas in an engine having the same cylinder dimensions, although the calorific power is only about one-fourth of the lighting gas. The relative powers which can be obtained from different kinds of producer gas in the same engine are given in Table XIII. on p. 138. For engine work it is more important to ensure that the heat of the gas shall be used to the best advantage, and, as has been shown in Chapter VI., higher compressions can be used with gases of comparatively low calorific power, and a greater proportion of the heat of combustion of the gas can therefore be converted into useful work. The calorific power of the gas supplied to an engine should not vary much from its mean value; excessive variations can be detected if the calorific power is determined from time to time by one of the methods described below.

For the successful application of producer gas to furnace and heating work it is often necessary that the calorific power should not fall below a certain minimum value, and makers of gas-producer plants are frequently required to give a guarantee of this kind. It is therefore important to have some ready means of determining the calorific power from time to time. We will therefore describe the principal methods which are in use for the experimental determination of the calorific powers of solid fuel and of producer gas.

The determination of calorific power consists in the measurement of the quantity of heat given out during the combustion of a known small quantity of the fuel. This is accomplished by means of an apparatus called a "calorimeter." The heat given out by the combustion of the fuel is used to heat water, and the quantity of heat is known from the weight of water heated and its rise in temperature.

The calorific power of solid fuels is most accurately determined by burning them in compressed oxygen in a bomb calorimeter. In calorimeters of this type a known weight of the fuel to be tested is placed in a capsule or crucible which is supported in the interior of a strong metal vessel. The latter is tightly closed, and oxygen is forced into it until the pressure is about 25 atmospheres. It is then immersed in a known weight of water contained in a suitable vessel; the fuel is ignited electrically, and the rise in temperature of the water is noted. The heat given out by the combustion of the fuel is equal to the heat required to raise the temperature of the water and the calorimeter itself through the observed range.

The construction of the calorimeter and the details of the method may be illustrated by reference to the Mahler-Donkin bomb calorimeter, which is shown in section in Fig. 68. This is a modified form of the Mahler bomb calorimeter. The bomb itself is capable of withstanding very high pressures; it is constructed of a non-corrosive metal and is gold-plated inside in order to resist the action of the nitric and sulphuric acids formed during the combustion. The cover is held in place by three studs and nuts, the joint being made with a packing of lead wire. This cover carries a valve for the admission of oxygen, also a metal holder which supports the platinum crucible in which the fuel is placed.

A metal rod passes through an insulating plug in the cover of the bomb, and a fine platinum wire (about 1 mm. diameter) is connected to the lower end of the rod and completes a battery circuit through the coal in the crucible. One terminal of the battery is connected to the insulated rod, and when the second

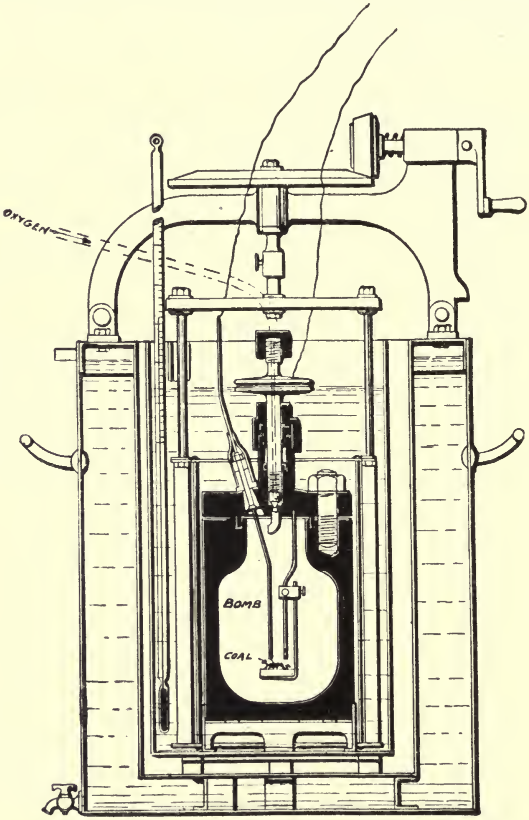

Fig. 68.—Mahler-Donkin bomb calorimeter.

terminal is connected to any point of the cover a current passes through the platinum wire and fuses it, at the same time igniting the fuel. The bomb is placed within a brass water-vessel which is provided with an arrangement of paddles rotated by means of a handle. The water-vessel is itself placed on brass supports within an annular water-jacket. The temperature of this water-jacket remains practically constant during an experiment, and the narrow air-space between the two water-vessels ensures that no heat shall pass from one to the other except by radiation. The water-jacket is provided with an accurate thermometer, so that its temperature can be kept uniform or any variation noted.

In making a determination about one gram of the dry powdered fuel is weighed accurately in the crucible, and the latter is placed in its support with the igniting wire passing through the fuel; the cover is then placed on the bomb and tightly screwed down. The valve is connected to an ordinary cylinder of compressed oxygen, and oxygen is slowly admitted to the bomb until the pressure reaches 25 atmospheres. A special regulating valve and pressure gauge, mounted on a separate stand, are connected between the bomb and the oxygen cylinder, so that the oxygen can be admitted slowly and the pressure in the bomb observed. If the oxygen is admitted too rapidly there is a risk of some coal being blown out of the crucible; apart from this, a rapid increase of pressure in the bomb would cause a rise of temperature. The charged bomb is placed in the water-vessel and a known weight of water, sufficient to cover it completely, is poured in. The water is stirred and its temperature noted. When the temperature is constant and the same as the temperature of the water-jacket the fuel is ignited by completing the battery circuit, and the temperature of the water is observed at short intervals until it has reached a maximum and begun to fall. The maximum temperature attained is carefully noted. The combustion of the fuel is very rapid, but two or three minutes must elapse before the maximum temperature is reached, as the heat must pass from the gaseous products of combustion through the metal walls of the bomb. The stirring must be continued until the maximum temperature has been observed.

Let t_1° C. be the temperature of the water before ignition of the fuel;

„ t_2° C. be the maximum temperature observed;

„ w grams be the weight of fuel taken;

„ W_1 grams be the weight of water in the water vessel;

Let W_2 grams be the water equivalent of the calorimeter (see below);
„ P be the calorific power of the fuel (in calories per kilogram, or in small calories per gram).

Then the heat given out by the combustion is $P \times w$ small calories, and this quantity of heat has raised the temperature of W_1 grams of water through $t_2 - t_1$ degrees. Certain parts of the apparatus have also been heated, and the quantity of heat required for this is determined once and for all by a separate experiment. It is W_2 small calories for each degree rise of temperature. The heat evolved by the combustion is therefore—

$$W_1(t_2 - t_1) + W_2(t_2 - t_1) \text{ small calories;}$$

and for the calculation of the calorific power we have—

$$P \times w = (W_1 + W_2) \times (t_2 - t_1)$$

where all the quantities are known except P. Therefore—

$$P = \frac{(W_1 + W_2) \times (t_2 - t_1)}{w}$$

The constant quantity W_2, called the "water equivalent" of the calorimeter, is determined by making a similar experiment with a fuel of known composition. Fused naphthalene is suitable for this purpose. Using the same letters as before, we again have—

$$P \times w = (W_1 + W_2) \times (t_2 - t_1),$$

but now P is known (9692 calories for naphthalene) and W_2 is the quantity required, so that—

$$W_2 = \frac{P \times w}{t_2 - t_1} - W_1.$$

A determination of the calorific power carried out in this way will give a result correct to within 0·5 per cent. of the true value, and this is sufficiently accurate for most purposes. When greater accuracy is desired corrections must be made for the heat lost by radiation from the water-vessel before the maximum temperature is reached, and for the heat evolved owing to the formation of nitric acid in the bomb during the combustion. The former correction may be dispensed with if the temperature of the water at the beginning of the experiment is adjusted so that the temperature of the water-jacket is midway between t_1 and t_2. The water in the vessel then receives heat by radiation during the first part of the experiment and loses an equal amount during the latter half.

When coal is burned under ordinary conditions no nitric acid is formed; the heat due to its formation in the bomb should therefore be deducted from the observed calorific power. In order to make this correction it is necessary to wash out the bomb after the experiment, and to determine by titration the quantity of nitric acid which has been formed. This correction is in the opposite sense to the correction for heat lost by radiation; and the two errors nearly balance one another, so that if both are neglected the result obtained is within 0·5 per cent. of the true value. For detailed information as to the method of making these corrections when necessary the reader is referred to Mahler's "Etudes sur les Combustibles."

For less accurate determinations of the calorific power of solid fuels, many calorimeters have been devised in which the combustion takes place in oxygen at atmospheric pressure. These differ in the details of their construction, but the principle may be described without reference to any particular form of calorimeter. The fuel is contained in a crucible which is supported inside a metal or glass enclosure forming the combustion chamber, and this is immersed in water in the calorimeter. The fuel is ignited either electrically or by some other suitable means, and oxygen at atmospheric pressure is passed into the enclosure to maintain the combustion. The oxygen is delivered from a tube just above the open mouth of the crucible; the progress of the combustion is watched (by an arrangement of mirrors if the enclosure is an opaque metal vessel), and the supply of oxygen is regulated accordingly. Before escaping into the air the products of combustion are made to give up their heat to the water in the calorimeter either by passing through a coil of metal pipe immersed in the water or by bubbling through the water.

The disadvantage of calorimeters of this type is that it is difficult to ensure complete combustion and complete cooling of the products. The success of their working depends largely upon the care exercised in regulating the supply of oxygen during combustion: if the oxygen is admitted too rapidly the products may not give up all their heat to the water before they escape from the calorimeter, but if the current of oxygen is too slow there will be smoke, and part of the volatile matter of the fuel will escape combustion. Often too a small amount of carbon is left unburnt in the crucible.

Of the many calorimeters based upon this principle two of the best known are the W. Thomson and the Fischer calorimeters.

A recent modification is that of Rosenhain, for which it is claimed that results can be obtained which are quite accurate enough for industrial purposes.[1] Apart from details of construction the essential modification in this calorimeter is that instead of burning the powdered fuel in a crucible it is compressed into a small briquette, which stands upon a flat porcelain plate; in this way the oxygen has readier access to the burning fuel, and experiments show that the amount of unburnt carbon is only 0·3 per cent. Water is admitted to the combustion chamber after the fuel has been burnt and before the final temperature is read, so that all parts of the calorimeter are quickly brought to the same temperature.

A third type of calorimeter for solid fuel is that in which the powdered coal is mixed with substances rich in oxygen, so that when ignited the mixture burns without any supply of gaseous oxygen being required. The Lewis Thompson calorimeter which is based upon this principle has been largely used in this country on account of its simplicity. The results obtained with it are, however, unreliable, and it should be used only where a rough approximation is sufficient. In this calorimeter the coal is mixed with suitable quantities of powdered potassium chlorate and nitrate, and the mixture is put into a small copper cylinder. This is supported inside a copper vessel which forms the combustion chamber, and the latter is immersed in water. The combustion is started by means of a fuse; the products of combustion leave the combustion chamber through a number of small holes near the bottom and bubble through the water in the calorimeter. Water is admitted to the combustion chamber before the final temperature is observed. With this calorimeter a considerable proportion of the coal is always left unburnt, and

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[1] *Philosophical Magazine*, 1902, vol. iv. p. 457.

to get any approach to accuracy it is necessary to recover the unburnt coal from the water after the experiment and to determine its amount. Practically this makes the determination very troublesome, and it is usual to neglect this correction. The results obtained may then be considered as comparative if the fuels tested are similar. The amount of unburnt carbon is, however, much greater with anthracite and coke than with coals rich in volatile matter, so that the results cannot be compared with one another when different kinds of fuel are tested.

The results obtained with calorimeters of these three types have been carefully compared by Messrs. Brame and Cowan,[1] and also quite independently by Drs. Gray and Robertson.[2] These authors are agreed that to obtain accurate results a bomb calorimeter should always be employed. The Lewis Thompson calorimeter and the calorimeters using oxygen at atmospheric pressure always give low results. The results obtained may be summarised as follows:—

DIFFERENCES FROM BOMB RESULTS (PER CENT.).

	Brame and Cowan.	Gray and Robertson.
Lewis Thompson calorimeter .	– 6·2 to – 1·8 [3]	– 13·0 to – 0·9
Fischer calorimeter	– 5·7 to – 2·6	not tested
W. Thomson calorimeter . .	– 6·9 to – 1·8	– 2·9 to – 0·7

Gray and Robertson, however, conclude that the W. Thomson calorimeter will give results sufficiently accurate for industrial purposes if the supply of oxygen is carefully regulated and the water equivalent of the calorimeter determined by an experiment with a coal of known calorific power. The same sources of error are present in the determination of the water equivalent as in subsequent determinations of calorific power. The number thus obtained for the water equivalent is in excess of the truth, and this approximately balances the various losses which occur in an

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[1] *Journal of the Society of Chemical Industry*, 1903, vol. xxii. p. 1230.

[2] *Ibid.*, 1904, vol. xxiii. p. 704.

[3] In these experiments allowance was made for the carbon which escaped combustion.

actual determination. Working in this way, the values obtained with different coals differed from the bomb results by $-1{\cdot}8$ to $+0{\cdot}5$ per cent. only.

It should be noted that in all determinations of the calorific power either the sample tested should be dried or the percentage of moisture in it should be determined at the time when the test is made. The percentage of moisture in coal varies with the humidity of the air; the calorific power should therefore refer to the *dry* fuel, and if the amount of moisture in the fuel at any time is known the value of the calorific power can be calculated accordingly. Thus if the calorific power of the dried fuel is 8000 calories per kilo, and if the sample contains 3 per cent. of moisture, the calorific power of the sample is $8000 \times 0{\cdot}97 = 7760$ calories per kilo.

The calorific power of solid fuels can also be calculated approximately from the results of a chemical analysis. Various formulæ have been put forward for this purpose, but as the direct determination by the bomb calorimeter is a much simpler operation than the ultimate chemical analysis, and gives a more reliable value for the calorific power, it will be unnecessary to discuss these and we give only one of them. According to Mahler,[1] the calorific power is equal to $81{\cdot}4 \times C + 34{\cdot}5 \times H - 30(O + N)$ calories per kilo, where C, H, O and N are the percentages of carbon, hydrogen, oxygen and nitrogen respectively in the dry fuel.

Mahler's experiments show that this formula may be used for any fuel of vegetable origin (peat, lignite, coal, etc.), and that the result obtained for the calorific power is within 3 per cent. of the true value. For ordinary coal the error is much less than this.

As the "proximate analysis" of fuel is simple and is often carried out in order to ascertain whether a fuel is suitable for a given purpose, it will be useful to describe a method by which the results so obtained can be used for a fairly accurate calculation of the calorific power. The formula given by Goutal[2] is—

$$\text{Calorific power} = 82 \times C + A \times V \text{ calories per kilo,}$$

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[1] "Etudes sur les Combustibles," p. 63.

[2] *Comptes Rendus*, 1902, vol. 135, p. 477.

where C is the percentage of fixed carbon in the fuel,
V is the percentage of volatile matter (exclusive of moisture),
and A is a coefficient depending upon the percentage of volatile matter in the fuel.

The values of the coefficient A are given in Table XXIV.

TABLE XXIV.—VALUE OF COEFFICIENT A IN GOUTAL'S FORMULA.

V′.	A.	V′.	A.
Per cent.	Calories.	Per cent.	Calories.
1 to 5	100	23	105
5	145	24	104
6	142	25	103
7	139	26	102
8	136	27	101
9	133	28	100
10	130	29	99
11	127	30	98
12	124	31	97
13	122	32	97
14	120	33	96
15	117	34	95
16	115	35	94
17	113	36	91
18	112	37	88
19	110	38	85
20	109	39	82
21	108	40	80
22	107		

In this table V′ is the percentage of volatile matter in the combustible portion of the fuel, *i.e.* supposing the moisture and ash to have been removed. The value of V′ is therefore—

$$\frac{100 \times V}{C + V}.$$

The following example is given to illustrate the use of the formula:—

The analysis of a sample of coal gave the following results:—

Fixed carbon	76·4	per cent.
Ash	11·0	„
Moisture	1·1	„
Volatile matter, other than moisture	11·5	„
Total . .	100·0	„

The value of V′ is $\frac{11{\cdot}5 \times 100}{76{\cdot}4 + 11{\cdot}5} = 13{\cdot}1$.

Referring to Table XXIV., we see that the corresponding value of A is 122 The calorific power is therefore—

$$82 \times 76{\cdot}4 + 11{\cdot}5 \times 122 = 7668 \text{ calories per kilo,}$$

or in round number 7670 calories per kilo.

According to Mahler this formula gives results for bituminous and semi-bituminous coals which are usually within 1 per cent. of the results obtained with the bomb calorimeter. With anthracite coals, which contain very little volatile matter, and with fuels rich in oxygen and containing a high percentage of volatile matter, *e.g.* lignite, the error is greater and the formula should only be regarded as approximate.

Since the percentage of volatile matter in the coal is not a very definite quantity the value obtained depending to some extent upon the exact method used in the determination (see p. 208), it is necessary in using Goutal's formula to follow a specified procedure. According to Mahler the following method should be used:—

Five grams of the coal are placed in a covered crucible of about 30 c.c. capacity and heated sharply over a Berzelius' rose burner. The flame should completely surround the crucible, and after the volatile matter has ceased to burn at the top of the crucible the heating should be continued for about three minutes. The loss of weight is due to the loss of volatile matter and moisture, and the quantity of the latter must be deducted.

The calorific power of coke may be calculated approximately if the percentages of ash and moisture are determined. According to Butterfield,[1] the calorific power is—

$$80{\cdot}8 \times (98 - \text{percentage of ash and moisture}).$$

This is equivalent to the assumption that the coke is made up of carbon, ash, and moisture, together with 2 per cent. of oxygen and nitrogen. The small amount of hydrogen in the coke is not taken into account.

The apparatus generally used for determining the calorific power of gas is Junkers' calorimeter, which is shown in Figs. 69,

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[1] "Chemistry of Gas Manufacture," p 316.

70 and 71. Gas is burned at a constant rate at the burner, and the heat given out is taken up by a constant stream of water flowing through the calorimeter. The measurements required are the volume, V, of gas consumed while a weight, W, of water passes through the calorimeter, and the temperatures t_1 and t_2 of the water as it enters and leaves the calorimeter. The measurements are not taken until the gas has been burning and the water running for some time, so that the temperature t_2 of the water leaving the calorimeter has reached a steady value. There is, therefore, no alteration in the temperature of the calorimeter itself during a test, and the heat given out by the combustion of a volume V of the gas is equal to the weight of water W multiplied by its rise in temperature. The calorific power of the gas is the heat given out by the combustion of unit volume, and we thus have—

$$\text{Calorific power} = \frac{W \times (t_2 - t_1)}{V}.$$

The calorimeter is constructed so that the loss of heat by radiation during a test is very small; and in all ordinary work this may be neglected.

The construction of the calorimeter can be seen from Figs. 69 and 70, which show the vertical section and the sectional plan respectively. The cylindrical combustion chamber **28** is surrounded by an annular copper water-jacket **15**. The burner **27** is placed in the combustion chamber, and the products of combustion pass through a number of tubes **30** extending from the top to the bottom of the water-jacket, and escape from the products outlet **32**. Cold water from the supply funnel **3** enters the water-jacket near its base and passes up outside the tubes, taking up the heat from the products. It is well mixed by the discs **17** in the neck of the calorimeter, and after passing the bulb of the thermometer **43** it escapes from the overflow funnel **20**. The water supply funnel **3** is provided with a strainer **2**, and is so constructed as to maintain a constant head of water. The amount of water passing through the calorimeter is regulated by the cock **9** and remains constant during an experiment. The temperature of the cold water as it enters the jacket is measured by the thermometer **12**.

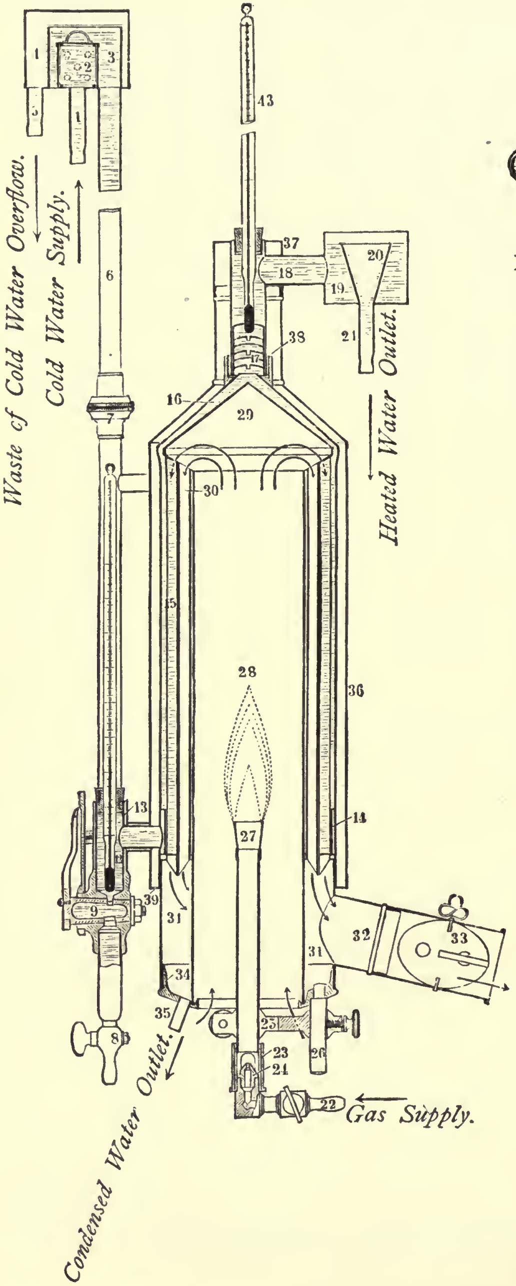

Fig. 69.—Junkers' gas calorimeter—vertical section.

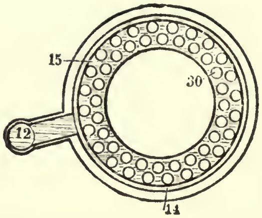

Fig. 70.—Junkers' gas calorimeter—sectional plan.

An air-jacket **36**, surrounding the water-jacket, prevents loss of heat by radiation. A valve **33** in the products outlet is used to regulate the draught through the calorimeter, and a thermometer can be inserted in the products outlet so that the temperature of the products may be observed.

Fig. 71 shows the complete apparatus set up for making a determination of the calorific power. The gas to be tested is measured by a small wet meter provided with a thermometer. It is also best to pass the gas through a governor to ensure a steady pressure at the burner; and a water column pressure gauge indicates the pressure above atmospheric at which the gas is measured. In making an experiment the water is set flowing through the calorimeter and allowed to run to waste; the gas is then lighted at the burner and the supply adjusted to about 700 liters (25 cub. ft.) per hour. The water supply is then adjusted by means of the cock 9, so that the rise in temperature of the water in flowing through the calorimeter is from 10° to 20° C. There should always be some water running to waste from the

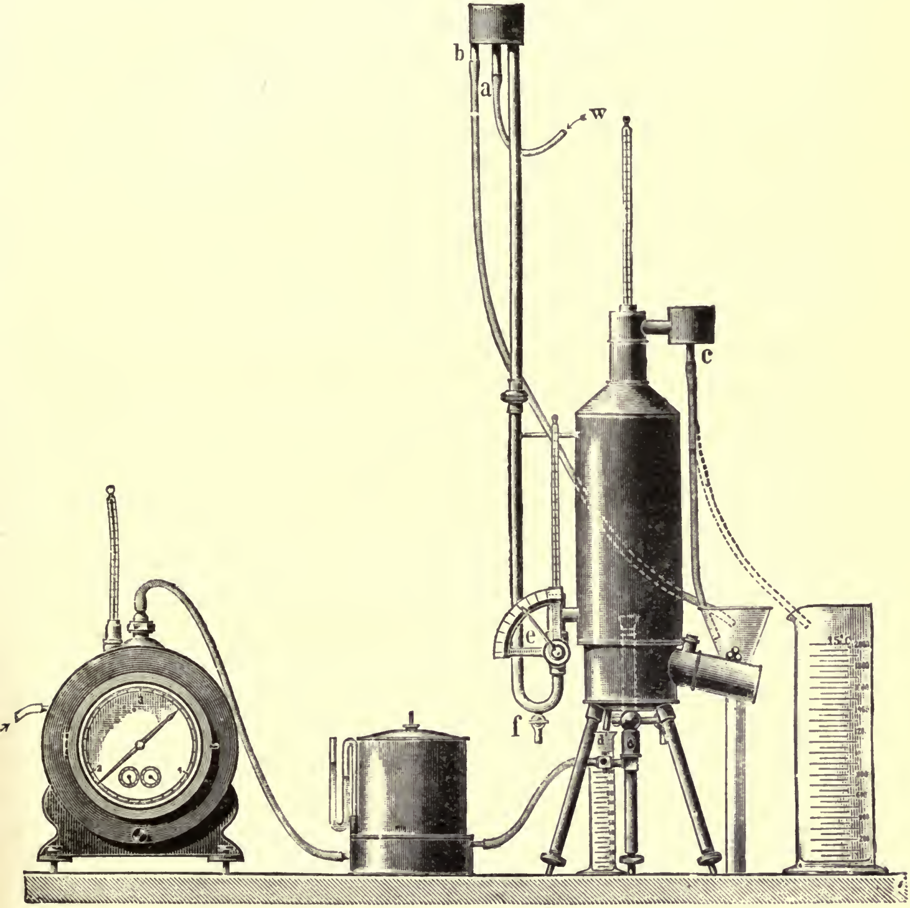

Fig. 71.—Gas calorimeter with meter, governor, etc.

overflow tube **5.** When the thermometers are steady the determination is made by observing the quantity of gas burnt, as shown by the meter, while two liters of water pass through the calorimeter. To do this the hot water from the overflow funnel **C** is collected in a glass vessel of 2 liters capacity, beginning when the pointer of the gas-meter passes the zero on the dial; when the water reaches the 2-liter mark the gas is turned off and the meter read again. While the water is being collected five or six readings of the thermometer **43** are taken at regular intervals. The average of these is the temperature t_2 of the hot water. The temperature of the cold water is read by the thermometer **12** at the beginning and end of the experiment, and the mean of these two readings is the temperature t_1 of the cold water. The temperature and pressure of the gas and the height of the barometer are also observed. From these data the calorific power of the gas can be calculated. Thus the results of a test of producer gas were as follows :—

Volume of gas recorded by meter 21·72 liters (0·767 cub. ft.) while 2 liters of water passed through the calorimeter.

Temperature of gas at meter, 17° C.

Height of barometer, 75·2 cms.

Pressure of gas above atmospheric, 4 cms. water column.

Temperatures of cold-water supply, 9·20 and 9·20; mean $t_1 = 9{\cdot}20°$ C.

Temperatures of hot-water overflow, 21·78, 21·74, 21·70, 21·60, and 21·73; mean $t_2 = 21{\cdot}71$.

The rise in temperature $t_2 - t_1$ is 12·51° C.

The quantity of heat given out during the combustion of 21·72 liters (0·767 cub. ft.) of gas is therefore $2 \times 12{\cdot}51 = 25{\cdot}02$ calories (99·28 Brit. T.U.), and the calorific power of the gas is $\frac{25{\cdot}02}{0{\cdot}02172} = 1152$ calories per cubic meter, or $\frac{99{\cdot}28}{0{\cdot}767} = 129{\cdot}4$ Brit. T.U. per cubic foot.

The result so obtained is the calorific value of the gas supplied to the meter; the volume of gas was measured at a temperature $t°$ C., and at a pressure equal to the barometric height h_1, plus the pressure due to a water column of height h_2 as measured by the pressure gauge on the meter, and minus the pressure of aqueous vapour in the gas. These pressures and temperatures vary in different tests; it is therefore always necessary to calculate from the above data the calorific power of unit volume of the gas when the gas is measured at the standard temperature and pressure (0° C. and 760 mm. of mercury), the gas being *dry, i.e.* free from water vapour. The method of making this correction is as follows:—

Let V_1 be the volume of gas registered by the meter;
V_0, the volume of gas at standard temperature and pressure;
$t°$ C., the temperature of the gas passing through the meter;
h_1, the height of the barometer;
h_2, the reading of the gas pressure gauge on the gas-meter;
h_3, the pressure of saturated water vapour at the temperature t, expressed in the same units as h_1, viz. millimeters or inches of mercury.

The pressure due to a water column of height h_2 is the same as that due to a column of mercury of height $h_2 \times 0{\cdot}0736$.

The actual pressure of the gas when measured by the meter was therefore $(h_1 + 0{\cdot}0736 \times h_2 - h_3)$ millimeters or inches of mercury. Then—

$$V_0 = V_1 \times \frac{(h_1 + 0{\cdot}0736 \times h_2 - h_3) \times 273}{760 \times (273 + t)},$$

if the temperature is measured on the Centigrade scale and the pressures in millimeters of mercury;[1] or—

$$V_0 = V_1 \times \frac{(h_1 + 0{\cdot}0736 \times h_2 - h_3) \times 491{\cdot}4}{29{\cdot}92 \times (459{\cdot}4 + t)}$$

if the temperature is measured on the Fahrenheit scale, and the pressures in inches of mercury.[1]

The volume V_0 must then be used instead of V_1 in calculating the calorific power from the figures obtained in the test.

The calorific power of the gas at standard temperature and pressure is clearly $\frac{V_1}{V_0}$ × the observed calorific power P_1, so that

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[1] See Appendix B, p. 268.

the correction may equally well be made by multiplying the observed calorific power by either—

$$\frac{760 \times (273 + t)}{(h_1 + 0{\cdot}0736 \times h_2 - h_3) \times 273}$$

$$\text{or } \frac{29{\cdot}92 \times (459{\cdot}4 + t)}{(h_1 + 0{\cdot}0736 \times h_2 - h_3) \times 491{\cdot}4}$$

according to the system of measurements employed.

In the example given above the barometric height was 752 millimeters, the gas pressure gauge gave a reading of 40 millimeters above atmospheric pressure, and the temperature of the gas was 17° C. The gas passing through the wet meter is saturated with water vapour, and the maximum pressure of water vapour at 17° C. is 14·4 millimeters (see Table XXVIII., Appendix B).

The corrected volume of the gas is therefore—

$$21{\cdot}72 \times \frac{752 + 40 \times 0{\cdot}0736 - 14{\cdot}4}{760} \times \frac{273}{273 + 17} = 19{\cdot}92 \text{ liters}$$

and the calorific power is—

$$1152 \times \frac{21{\cdot}72}{19{\cdot}92} = 1256 \text{ calories per cubic meter,}$$

the gas being measured when dry and at standard temperature and pressure.

In stating the calorific power of gas a distinction is often made between the "higher" and "lower" values, or "gross" and "nett" calorific powers. The gross calorific power is the result determined as described above, and represents the heat obtained by burning unit volume of the gas and cooling the products to the same temperature as that of the gas before combustion, *i.e.* usually to atmospheric temperature. The products of combustion are carbon dioxide and steam in varying proportions, which are mixed with the nitrogen originally present in the gas and that present in the air used for combustion. In cooling the mixture of gases to atmospheric temperature the steam is practically all condensed and its latent heat is given up. It is sometimes considered that for practical purposes this amount of heat is not available for useful heating, since it is only evolved when the products are cooled below 100° C., while in practice the products of combustion are always led away from the furnace or other heating apparatus at a temperature much higher than this. The latent heat of the steam in the products of combustion is therefore deducted from the gross calorific power, and the value thus obtained is called the "lower value" or the "nett calorific power" of the gas. No general statement can be made as to which value of the calorific power should be given, because this depends upon the purpose for which the figure is to be used. In making a general statement of the properties of the gas both values should therefore be given, and each will be useful for certain purposes. For example, in stating a heat balance-sheet for a gas-producer or in calculating its efficiency, the gross calorific power should be taken; for in these cases the manner in which the heat of combustion of the gas is utilised has not to be considered. The fact that the gas-engine or furnace rejects the products of combustion at a high temperature, so that the steam is not condensed, must not be counted against the producer. On the other hand, if it is desired to consider the efficiency of a complete gas installation, either for power or heating, *i.e.* to compare the heat of combustion of the solid fuel with the useful effect obtained in an engine or gas-fired heating apparatus, then, in consequence of the fact that the products of combustion are not completely cooled, the producer gas which yields least steam in its products of combustion will (if the products are rejected at the same temperature) give the best result.

As regards furnace work, it should be remembered that a considerable proportion of the hydrogen in the gas is derived from the volatile constituents of the fuel and not from the decomposition of steam supplied to the producer, so that even when the fuel is burnt direct in a furnace there is steam in the products and its latent heat is lost. The apparent disadvantage of gas-firing from this point of view is therefore not so great as the difference between the gross and nett calorific powers would seem at first sight to indicate.

In the Junkers calorimeter the steam in the products condenses and the water formed runs out from the overflow **35** (Fig. 69) at the base of the instrument. In making a test with the calorimeter the water which drips from **35** (Fig. 69) is collected in a graduated glass vessel d (Fig. 71) while a convenient volume of gas is burnt.

The amount of heat liberated when one kilo of steam at $t°$ C. is condensed to water is $(606{\cdot}5 - 0{\cdot}695 \times t)$ calories, and for the ordinary atmospheric temperature it is sufficiently accurate to take this as 600 calories. Hence if unit volume of the gas (liters or cubic feet) yields x c.c. of water at the overflow, the quantity of heat to be deducted from the gross calorific power is $x \times 0{\cdot}600$ calories, or $x \times 2{\cdot}38$ Brit. T.U.

In the experiment described above, 50 liters of the gas yielded 5·5 c.c. of condensed water. 1 c.m. of gas would therefore yield $20 \times 5{\cdot}5 = 110$ c.c., and the correction to be applied is $110 \times 0{\cdot}600 = 66$ calories.

The nett calorific power of the gas is therefore 1152 − 66, or 1086 calories per c.m. at the observed temperature and pressure, or $1086 \times \frac{21{\cdot}72}{19{\cdot}92} = 1184$ calories per c.m. at standard temperature and pressure.

In British units, if 2 cub. ft. of the gas yield 6·2 c.c. of condensed water, the amount to be deducted from the calorific power of the gas at the observed pressure and temperature is $3{\cdot}1 \times 2{\cdot}38$, or 7·4 Brit. T.U.

For very accurate work the temperature of the products should be observed at the outlet **32**, and the water and gas supplies to the calorimeter should be adjusted so that the temperature of the products is the same as that of the atmosphere. When this is not done the products are usually cooled below the temperature of the atmosphere (since the water supply is generally below atmospheric temperature), and heat is therefore taken up by the calorimeter, not only from the products after they have been cooled to atmospheric temperature, but also from an unknown quantity of air which passes through the calorimeter in consequence of the draught induced by the flame. The result obtained for the calorific power is therefore slightly in excess of the true value, but in ordinary working this difference may be neglected.

The principle used in this calorimeter is very different from that of the various calorimeters used for solid fuel. In the latter a definite limited quantity of the fuel is burnt in all cases, and a definite limited quantity of water is heated; while in the former, the combustion is continuous and there is a constant stream of water through the calorimeter. This principle, which is very convenient for gaseous fuels, was introduced by Hartley in his gas calorimeter. There are several other calorimeters based on the same principle besides that of Junkers. In the modification designed by Mr. Dowson there are two concentric annular water-jackets, the inner forming the walls of the combustion chamber. The products leave the top of the combustion chamber and pass down the annular space between the two water-jackets, while the water passes upwards through each jacket, the two streams of water mixing at the top of the calorimeter. In this way the products are efficiently cooled, and the construction is much simplified by avoiding the use of numerous tubes, the joints of which often give trouble.

The gas-calorimeter of Professor C. V. Boys works upon the same principle of continuous combustion and continuous flow; it was specially designed for testing the calorific power of lighting gas, and has been adopted by the Metropolitan Gas Referees for that purpose. With a suitable burner it is, however, capable of giving accurate results with producer gas. In this calorimeter, shown in section in Fig. 72, the water flows through a double coil **M N** formed of copper pipe surrounded by coils of copper wire, as in a motor-car radiator, so as to increase the heat-collecting surface. In this way the water content of the apparatus is reduced to a minimum, so that simultaneous readings of the inlet and outlet thermometers give the true rise of temperature. The hot water from the coil **M** passes through a coil of pipe around the hood **H** and thence through spiral passages in the temperature equalising chamber **K** to the outlet thermometer, which is situated at the same level as the inlet thermometer. The chimney **E** surrounding the flame is not directly cooled, except at the lower end, and there is no condensation upon it. The outlet for the water condensed from the products of combustion is at **F**; the instrument is filled with water up to this level before use, and this water is kept cool by the two lowest turns of the cooling coil. When out of use the body of the calorimeter is lifted by the lid **G** out of the casing **D**, and is placed in a similar vessel containing a very dilute solution of sodium carbonate; in this way the coils are preserved from corrosion by the acids in the combustion products.

The calorific power of gases can also be determined in the bomb calorimeter. For this purpose the crucible is dispensed with, and it is necessary to know the exact capacity of the bomb. This is easily found from the weight of water required to completely fill the bomb with the cover fastened on. To determine the calorific power of a gas the cover is bolted down and the air is exhausted from the bomb by a small air-pump. Gas is then

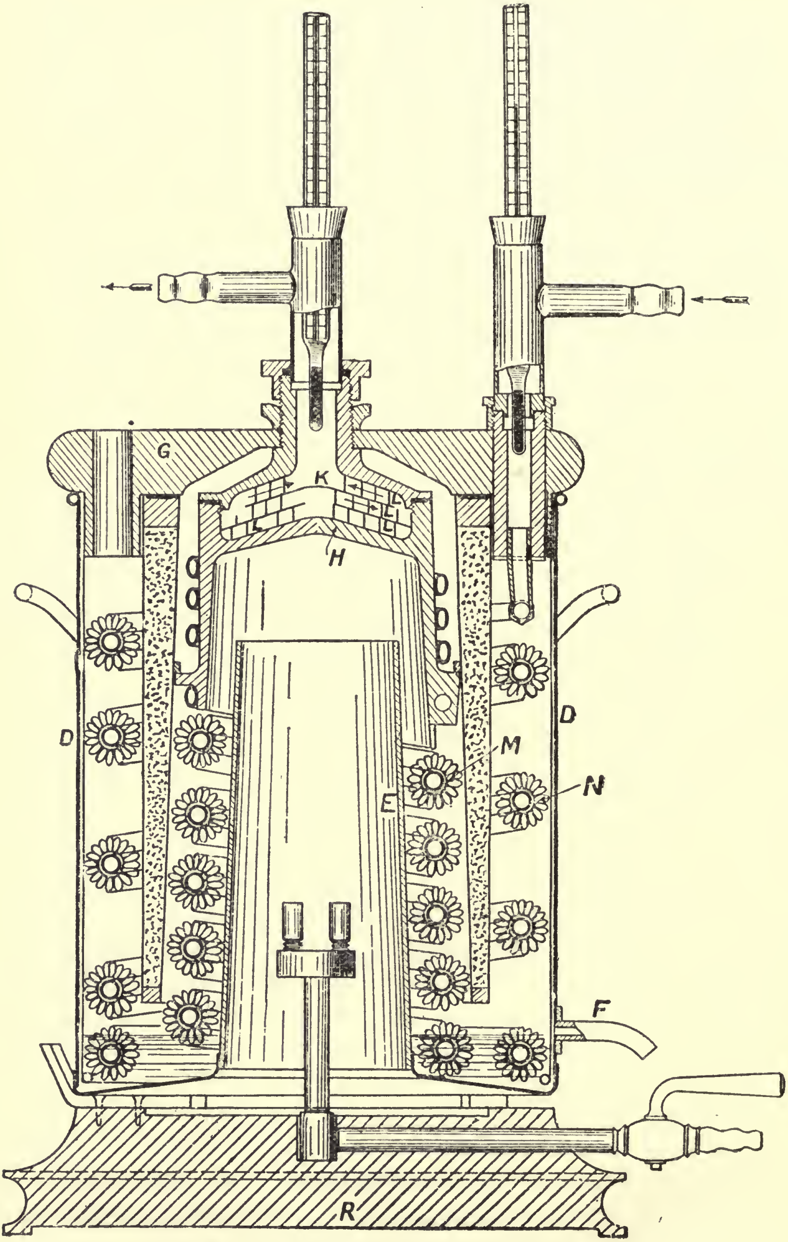

Fig. 72.—Boys' gas calorimeter—vertical section.

admitted and the bomb is again exhausted by the pump; this double exhaustion ensures all air being removed. The bomb is then filled with the gas to be tested, the height of the barometer and the temperature of the gas being noted. The gas should be saturated with water vapour; the bomb then contains a known volume of the gas at a known temperature and pressure. Oxygen is then slowly admitted till the quantity is sufficient for complete combustion of the gas. It is necessary to avoid too large an excess of oxygen or the mixture will not explode; it is found that for producer gas the pressure in the bomb should be raised to half an atmosphere, but for ordinary lighting gas 5 atmospheres is a suitable pressure. Pressures as low as half an atmosphere are most suitably measured by means of a mercury pressure gauge. After the bomb has been charged in this manner it is placed in water in the calorimeter, and the determination is carried out in the same manner as with solid fuel. The volume of gas taken is equal to the known capacity of the bomb, and must be reduced to standard temperature and pressure.

The bomb of Professor A. Witz differs considerably from the type of bomb calorimeter described above, and is suitable only for testing gases. This bomb is shown in section in Fig. 73. It consists of a steel cylinder, **A**, of about 250 c.c. capacity, with screwed end covers, **BB**, the joints being packed with oiled paper. The upper cover carries the igniter **C**, and the lower cover slopes downwards to the centre and is provided with a valve, **D**, at the lowest point. All the surfaces are nickel-plated to lessen the corrosive action of the gas. An explosive mixture of gas and air or oxygen is prepared by means of the glass bulb shown in Fig. 74. This may have a capacity of 250 to 500 c.c. It is filled with water, and the cock **A** is connected to the gas supply. The water is then allowed to run out at **B**, so that the bulb is completely filled with gas. This gas is passed into a bell jar which is inverted over water, and displaces some of the water with which the jar was filled. For producer gas an equal volume of air is added in the same way; for lighting gas seven volumes of air are added. To charge the bomb it is filled with mercury and placed in a mercury trough. The mixture from the bell jar is forced through a rubber tube, and fills the bomb by displacement of the mercury. The valve **D** is closed, and the bomb, which is now filled with the gaseous mixture at a pressure slightly above atmospheric, is removed from the mercury trough. On slightly opening the valve for an instant a little of the mixture escapes and the pressure falls to atmospheric. The capacity of the bomb and the proportion of gas in the mixture being known, the volume of gas in the bomb is known; the temperature and barometric height are

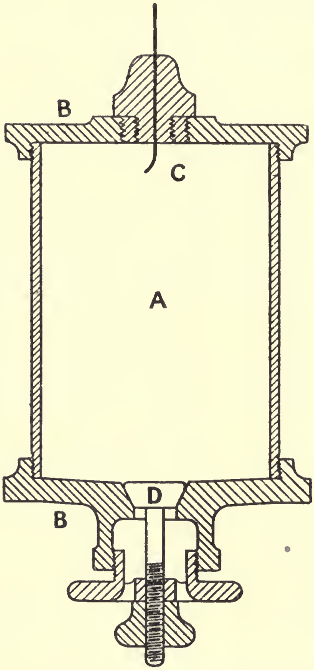

Fig. 73.—Witz bomb calorimeter.

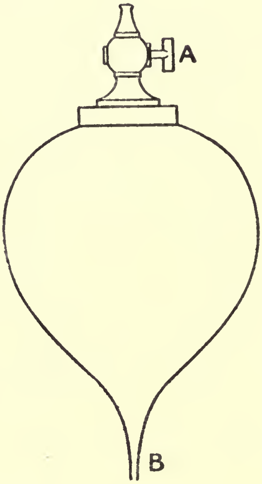

Fig. 74.—Glass bulb for explosive mixture.

observed when the bomb is charged. The bomb is immersed in a known weight of water in a suitable vessel, and the temperatures before and after explosion are observed, as in the case of the bomb calorimeter described for use with solid fuel.

The essential difference between the Witz bomb and the type used for solid fuels is that the former is charged only at atmospheric pressure. The quantity of gas used in each test is therefore very small, and the thermometer used to observe the rise in temperature must have a very open scale. The observed rise is only one or two tenths of a degree Centigrade.

When the calorific value of gas is determined in either type of bomb calorimeter the charge in the bomb before explosion is saturated with water vapour. The steam formed by the explosion will therefore be all condensed, and the result obtained is the gross calorific power of the gas when burnt at constant volume.

In a gas-engine the combustion takes place at constant volume, but when gas is burnt in the usual way the products of combustion are at atmospheric pressure. If the products of combustion occupy a smaller volume than that of the gas and air from which they are formed (the volumes being compared at the same temperature and pressure) work has been done by the pressure of the atmosphere, and the calorific power at constant pressure will be greater than the calorific power at constant volume by an amount of heat equivalent to the work done on account of the change of volume.

The change in volume can be calculated from the chemical composition of the gas; the difference between the two values of the calorific power can then be calculated; and the calorific power at constant pressure (the value which is usually referred to simply as the calorific power) can be got from the bomb result.

For producer gas the change in volume is not great, and the difference in calorific power due to this is less than 0·5 per cent. For ordinary purposes, therefore, it may be neglected.

In order to ascertain the nett calorific power from the result obtained in the bomb it is necessary to know the quantity of water formed during the combustion. This may be determined by a special experiment in which the carefully dried gas is passed through a tube containing copper oxide at red heat and the water formed is absorbed in weighed tubes containing calcium chloride. If the chemical composition of the gas is known the quantity of steam produced by the combustion of the gas can be calculated (see p. 251). When this quantity has been ascertained by one or other of these methods the nett calorific power can be calculated in the manner already explained (p. 244). The trouble involved in getting the calorific power at constant pressure and the nett calorific power from the result actually obtained in the bomb is a serious drawback to its use for gases, and it is generally more convenient to use a Junkers calorimeter or some other of the same type. The quantity of gas used in a test is much greater, and the determination is far more easily and rapidly made. The gas can be kept burning under the calorimeter, and when once the adjustments have been made and the temperature has become steady, tests can be made as often as desired, each determination occupying no more than about five minutes.

If the composition of producer gas is ascertained by analysis the calorific power can be calculated by means of the known values of the calorific powers of the combustible gases contained in it. This method is adopted when for any reason it is inconvenient or impracticable to obtain a supply of gas for use with the calorimeter. It is also the most suitable method when it is desired to obtain the average calorific power of the gas during a period of time. A sample of gas for analysis can be drawn off at a constant rate during any period, and subsequently analysed; but the determination of the calorific power by means of a calorimeter only gives the value for the gas actually burned during the test. When the producer gas made in a suction plant is to be tested there is no supply available for use with a calorimeter unless a suction pump or fan and a pressure regulator are specially installed; this is necessary in order to draw off gas from the main, where it is at reduced pressure, and deliver it at a constant pressure of 25 to 50 mm. of water at the testing meter. Where this cannot be done there is no special difficulty in taking a sample of the gas for analysis, and this method is generally adopted. The apparatus described in Chapter XIII. for collecting a sample of the gas can be used for a suction plant, as well as for those cases in which the pressure of the gas is slightly above that of the atmosphere.

The values for the calorific powers of hydrogen, carbon monoxide and methane are given in Table XXXII., Appendix B.

The calculation of the calorific power from the analysis of the gas may be illustrated by means of an example—

Composition of Gas (Per Cent. by Volume).

Hydrogen	16·2
Carbon monoxide	21·0
Methane	1·3
Carbon dioxide	8·5
Oxygen	0·2
Nitrogen	52·8
Total	100·0

The gross calorific power per cubic meter will be the sum of the quantities of heat given out by the combustion of the first three constituents—

Due to the hydrogen	0·162 × 3088 = 500	calories.
Due to the carbon monoxide	0·210 × 3046 = 640	"
Due to the methane	0·013 × 9545 = 124	"
Total	1264	calories per c.m.

The value in Brit. T.U. per cubic foot can be calculated in a similar way.

The calorific power can also be obtained from the analysis by means of Table XXXIV. in Appendix B.

The nett calorific power is calculated as follows:—

The volume of steam formed by the combustion of 1 c.m. of gas is—

0·162 c.m. due to the hydrogen,
and 2 × 0·013 = 0·026 c.m. due to the methane.
Total 0·188 c.m.

The latent heat of the steam formed by the combustion of 1 c.m. of hydrogen is 486·7 calories, and the number which must be deducted from the gross calorific power is 486·7 × 0·188 = 91·5 calories.

The nett calorific power of the gas is therefore 1264 − 91·5 = 1172·5 calories per cubic meter.

If the calorific power is expressed in Brit. T.U. per cubic foot, the calculation is as follows:—

The quantity of steam formed by the combustion of 1 cub. ft. of the gas is 0·188 cub. ft. (see p. 251).

The latent heat of the steam formed is—

$$0{\cdot}188 \times 54{\cdot}7 \text{ Brit. T.U.} = 10{\cdot}3 \text{ Brit. T.U.},$$

and this quantity must be deducted from the gross calorific power in Brit. T.U. per cubic foot.

CHAPTER XV

PRACTICAL NOTES

1. *Carbon Monoxide Poisoning.*—Although there are thousands of gas-plants in use, there have been few cases of poisoning or asphyxiation. It is, however, important that certain risks attending the use of producer gas should be fully recognised and provided against. We all know that precautions have to be taken when gunpowder, dynamite, high-tension electric currents, etc., are used; and in the same way those who use producer gas should know that certain precautions are necessary.

The only poisonous constituent of producer gas is carbon monoxide before it is burnt to carbon dioxide, and care must be taken that the unburnt gas is not inhaled. When the gas is taken direct from a producer to a furnace there is no risk of this occurrence unless there is a leak in the gas-main or flue which conveys the gas; the same may be said when a gas-engine is driven with producer gas. This is especially the case when a suction plant is used (provided that certain precautions are taken when starting the engine), because the gas in the main is below the atmospheric pressure when the engine is running. If the gas is used for heating purposes, with open burners, it is possible for unburnt gas to escape in the workroom if the attendant is ignorant or careless; the gas should be lighted as soon as it is turned on, and care should be taken to ensure complete combustion. For such work it is essential that the room in which the gas is used should be well ventilated. The risk of leaks from mains is increased when the gas is forced through at a high pressure; but the ordinary pressure in the distributing pipes of a factory does not exceed that of a column of water 40 to 50 mm. high.

Special care should also be taken not to enter any part of a plant before the gas has been completely expelled. In par. 9

we have described in detail the precautions which should be taken in connection with gasholders.

Carbon monoxide has the peculiar property of combining with the hæmoglobin of the blood, and when this occurs the blood corpuscles will not take up oxygen from the air and convey it to the tissues. According to Dr. Haldane,[1] air containing so small a percentage as 0·2 per cent. of carbon monoxide should be regarded as entailing risk to life. The danger in using this gas is increased because it is inodorous, and unless it is associated with some other gas or vapour which has a characteristic odour its presence cannot be detected by the nose.

"The first symptoms produced by breathing the gas are giddiness, weakness in the legs, and palpitation of the heart. If a man feels these symptoms he should at once move into fresh warm air, when in slight cases they will quickly disappear. Exposure to cold should be avoided, as it aggravates the symptoms. A man should not walk home too soon after recovery, as muscular exertion, when affected by the gas, is to be avoided. If a man should be found insensible or seriously ill from the gas, he should at once be removed into fresh warm air, and immediate information be sent to the oxygen administrator, a medical man being sent for at the same time."[2]

The first-aid measures to be adopted in cases of carbon monoxide poisoning are fresh air, artificial respiration, administration of oxygen, and the application of warmth; but medical aid should be summoned immediately. It is recommended that a cylinder of compressed oxygen, fitted with rubber tubing and a mouthpiece, should be kept in readiness in factories where this danger is likely to arise.

We think it well to add a special word of caution with regard to suction plants. It is true that gas cannot escape from the main while the engine is running, but when the engine is about to be started the producer is worked with a blower which sends gas at pressure to the engine. If through ignorance or carelessness

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[1] Report of Departmental Committee on Water-gas [C. 9164], 1899: Appendix A.

[2] Memorandum as to the Use of Water-gas in Factories, issued by the Home Office, September, 1904.

the attendant attempts to start the engine with the crank a complete revolution ahead of the correct position for starting, both the gas and air valves will be open; and if the blower is in operation, and gas is being blown through to the engine, it will pass through the gas-valve, the air-valve, and air-box into the engine-room. When starting an engine the attendant should, therefore, look to the lay shaft to see that the cams are not holding open the gas and air valves.

It is also obvious that in testing the gas near the engine it should not be allowed to escape unburnt into the engine-room, even when it may not be strong enough to burn.

2. *Working Two or More Producers Together.*—If suitable arrangements are made, there is no limit to the number of producers which can be worked together satisfactorily; but it is important that each one should be provided with a shut-off valve, or that the gas outlet pipe of each producer should be sealed in water. Apart from any question of convenience in working, each producer should be isolated in order that when one is not in use gas from the others cannot pass through it and escape.

3. *Depth of Fire.*—Not infrequently workmen have the mistaken idea that a gas-producer needs a comparatively shallow fire for a reduced output of gas; they think that if there is the same depth of fuel as for the maximum output there will be a greater consumption for a given volume of gas. The depth of fire should never be less than the minimum required to produce the necessary reactions, but within certain limits it is possible to make a reduced quantity of good gas with a less depth of fire than is required for the maximum output. It is, however, a mistaken idea to suppose that the consumption of fuel per unit volume will at any time be more or less than that required for the maximum rate of production, provided gas of the same composition is made; but if at any time the fire is less than the correct minimum depth an excess of carbon dioxide will be produced, and the consumption of fuel will be wasteful. In practice it is simplest and best to maintain the depth of fire required for the maximum rate of production, as it ensures the making of good gas without increasing the fuel consumption per unit volume.

In suction plants and in some pressure plants it is usual at starting to fill up the producer to the level of the feeding hopper, and never to let the top of the fire fall below the level at which the gas leaves the fuel. There is then always a store of fresh fuel in the container, which gradually descends as the fuel below burns away, and the depth of the fire is thus automatically kept constant whether the engine be working under a full or reduced load. This helps to secure uniformity in the quality of the gas, and it does not add to the fuel consumption. The top of the fire is at the level at which the gas leaves the column of fuel (*e.g.* see Figs. 37 and 38), and can only alter if the attendant allows the container to become empty and the fuel to burn away below this level.

In a pressure plant, if no fuel container is provided below the feeding hopper, the top of the fire should not be above the level of the gas outlet, nor should it be lower than is required for making good gas. It is a common practice to allow the depth of fire to decrease at the end of the day's run in order to facilitate the operation of clinkering on the following morning, and there is no objection to this if the depth is not reduced too far.

The depth of fire depends a good deal on the size of the producer and on the nature and size of the fuel. With anthracite in pieces about $1\frac{1}{2}$ to 3 ins. cube the fire should be 3 to 6 ft. deep, according to the size of the producer. With anthracite peas which pass through openings $\frac{3}{4}$ in. wide and over openings $\frac{3}{8}$ in. wide, the fire is usually from 2 ft. 6 ins. to 4 ft. deep, according to the size of the producer. With bituminous coal or with coke the depth of the fire should be greater than with anthracite.

4. *Removal of Condensed Moisture.*—Provision should always be made for removing condensed moisture from the pipes which convey producer gas, except in cases where hot gas is taken direct from a producer to a furnace. When a gasholder is used it is very important to keep the inlet and outlet pipes free from water, as also the distributing mains and the branches or connections to the burners or gas-engine for which the gas is to be used. As far as is possible the gas-mains should drain towards one common point, and the moisture which collects there can be allowed to flow away through an overflow pipe sealed in water; or if the level is too low for the water to flow away by

gravity provision should be made for removing it by a small pump.

Neglect of these simple precautions often leads to a stoppage of the gas supply, with its attendant troubles.

5. *Testing the Pressure of the Gas.*—When gas will not pass freely through the gas-plant and piping, the gas pressure should be taken at various points to locate the obstruction. An ordinary water-column **U** gas pressure gauge is generally used for this purpose, and in most cases it need not be more than about 300 mm. (say 12 ins.) long. In large installations it is convenient to lead small pipes from various points of the plant to gauges fixed in some convenient spot, preferably in the gas-house. Means should be provided for testing the pressure of the gas at or near the outlet of the producer, at the inlet and outlet of each separate scrubber or other part of the plant, and at any points in the gas-main where water may collect. When such permanent arrangements are made for testing it is simple to arrange the gauges and pipes so that the pressure of the gas above that of the atmosphere at any point of the plant can be observed, and also the difference between the pressures of the gas at any two points. To avoid risk of stoppage it is advisable (especially with large plants) to observe the pressures regularly, and any tendency for the pressure to increase beyond the normal amount should be at once investigated.

6. *Lining of Gas-producers.*—It is usual to line the inside of a gas-producer with firebricks, and it is most important that these bricks should be well set with thin joints of fireclay; it is also desirable that there should be a backing of sand or broken bricks mixed with fireclay between the firebrick lining and the iron casing. When the lining has been finished a small fire should be lighted in the producer to dry the brickwork gradually before it is subjected to the great heat which is developed when the producer is used for making gas. These precautions are necessary to prevent cracks in the brickwork through which air can pass; for if air mixes with the gas in the producer some of the gas is burnt, and this is not only wasteful but it dilutes the gas by increasing the proportion of nitrogen and carbon dioxide. When this occurs to any considerable extent blue flames may be seen inside the producer; they could not occur if there were no air

to burn with the gas. When the gas is analysed a small quantity of free oxygen is sometimes detected, which is a sure sign that air has mixed with the gas; this more often occurs with suction plants as there is naturally a tendency for air to be drawn in. For this reason all the joints in the ironwork should be attended to carefully.

7. *Test-flames.*—When a pressure plant is used for engine or heating work requiring uniformity in the quality of the gas it is often convenient to have a small test-flame burning continuously If the gas is at a constant pressure, as it would be from a gasholder, the attendant soon gets to know the height and appearance of the flame when the gas is good; the flame should be enclosed in a lantern, as it will then be steadier, and there can be a vertical scale behind it to denote more exactly the variations in height. The attendant should also notice the colour and character of the flame, which are useful guides.

With a suction plant it is not possible to keep a flame burning while the engine is working, as the pressure is reduced below atmospheric; but when the plant is started with a blower the gas is at a pressure above that of the atmosphere, and during the period of blowing it is best to have a test-cock on the outlet of the producer. As soon as gas will burn properly at this point the cock on the waste pipe should be closed, so that the gas may flow to the engine; and near the latter there should be a blow-off pipe and another test-cock. When the gas will burn properly at this cock the engine should be started, and immediately afterwards the blow-off pipe should be closed to prevent air being sucked in.

8. *Starting a Gas-fired Oven or Furnace.*—It seems obvious that when an oven or furnace is to be heated by gas the latter should not be turned on before a light is introduced; but this simple precaution is sometimes neglected, and the inevitable explosion occurs. In a large furnace it is usual to light some cotton waste soaked in petroleum, and to place it on the floor of the furnace near the gas inlet; or sometimes a shovelful of burning coal or coke is used instead. The gas should then be turned on gradually until there is a certainty that all gas admitted will be ignited.

In small ovens or other apparatus it is sufficient to use a taper, or some cotton waste soaked in petroleum fixed to the end of a rod.

Sometimes it is convenient to have a pilot light always burning in the oven (to ensure that the gas used for heating is always ignited) if there is any risk of the supply being interrupted, or of there being great fluctuations in the pressure.

9. *Gasholders.*—When gas is to be used for the first time after the erection or cleaning of the plant it is best to fill the gasholder with gas and then blow off the contents into the air without igniting the gas. Without this precaution there would be a mixture of gas and air in the parts of the plant, and there would be serious risk of explosion if the mixture were ignited.

When it is necessary to enter a gasholder after it has been used the procedure should be as follows:—

(*a*) Let the tank be full of water.

(*b*) Blow off all gas in the gasholder until the latter rests on the bottom of the tank.

(*c*) Draw the fire out of the producer and put on the doors; close the valve nearest the holder on the outlet main.

(*d*) Fill the gasholder with steam and air if the producer is of the steam-jet type. If there is no steam at pressure to act as an injector, fill the gasholder with air from a blower, and blow off the contents of the holder. Again fill and blow off, and repeat this operation a third time.

(*e*) After filling the gasholder with steam and air, or air only, and after blowing off the contents three times, take off the cover of the manhole on the top of the gasholder, and empty the water out of the tank.

(*f*) The gasholder and tank may now be entered.

It is important that the inlet and outlet pipes of the gasholder should be drained, and when syphon boxes are used they should be pumped clear of condensed moisture as often as is necessary.

10. *Steam Supply.*—When a producer is worked with a steam-jet air injector the pressure of the steam must be high enough to overcome the resistances opposed to the passage of gas through the various parts of the plant. The steam pressure necessary depends also on the size of the producer and the volume of gas required; it usually varies from 2 to 4 atmospheres (30 to 60 lbs. per square inch).

In practice, when gas is used for driving engines or for heating work of various kinds, it seldom happens that the consumption is at a constant rate; it is therefore desirable to approximate the rate of production to a varying rate of consumption. To effect this in a simple way Mr. Dowson introduced a method of governing the production by the rise and fall of the gasholder. His first arrangement was to blow off some steam and air from the lower part of the producer, as shown in Fig. 22, and as described on page 87. Later he adopted the method of regulating the admission of steam to the producer without blowing off steam or air. For this purpose the steam admission valve has a weighted lever which is attached to a wire cord running on pulleys; at the other end of the cord there is a weight suspended over the crown of the gasholder, and the length of the cord is adjusted so that when the gasholder is nearly full the weight rests on it and the weighted lever on the steam valve falls and closes, or partly closes, the valve. When the gasholder falls the weight suspended over it raises the weighted lever on the steam valve, and the full supply of steam enters the producer. In this way (within certain limits) the rate of production is governed automatically to suit a varying rate of consumption. This arrangement has the further advantage that it reduces the size of the gasholder required as less storage capacity is necessary.

11. *Overflow Water.*—When a gas-plant is near a drain it is easy to carry the overflow water to it; but the water should not be too hot, or vapours may rise from it which would pass the gratings or ventilators in the public roads or streets. In some cases there is no drain, and it also happens sometimes that there is a stream near the gas-plant which must not be polluted; the disposal of the overflow water is then a matter of some difficulty, and it will be well to consider the nature of the water which has to be disposed of.

When the fuel in the producer is burnt part of the sulphur remains in the ash as sulphate and the remainder is present in the gas chiefly as sulphuretted hydrogen. This gas is soluble in water and is partially absorbed by the scrubbing water; the remainder goes with the gas. We cannot estimate, even approximately, the proportion of the sulphur in the coal which is taken up by the scrubbing water, as it depends on so many factors—*e.g.* the manner in which the sulphur in the coal is combined (whether as pyrites or in organic combination), the efficiency of the scrubbing, the temperature of the scrubbing water, etc. However, for the purpose of an example we will assume that the fuel contains 1 per cent. of sulphur, and that half of it is ultimately found in the overflow water from the scrubber, chiefly as sulphuretted hydrogen.

With these assumptions, which are probably in excess of the truth, a 100 B.H.P. gas-plant working at full load, and using, say, 400 grams or 0·9 lb. of anthracite per B.H.P.-hour, would give about 200 grams (0·45 lb.) of sulphur in the overflow water each hour. If this cannot be allowed, care should be taken to use anthracite which does not contain more than 0·5 per cent. of sulphur. The quantity of the overflow water can also be reduced considerably if the gas from the producer is sufficiently cooled by passing through a series of pipes before it enters the scrubber.

In suction plants there is always a small quantity of air drawn in above the fire, and as it mixes with the hot gas it oxidises part of the sulphuretted hydrogen to sulphur dioxide. The latter is also soluble in water, so that the overflow water from the scrubber of a suction plant usually contains both sulphur dioxide and sulphuretted hydrogen dissolved in it.

APPENDIX A

(See Chap. VII., p. 130).

TABLE XXV.—TRIAL OF 30 B.H.P. SUCTION PLANT WITH ANTHRACITE.

	FUEL.					GAS.					Heat efficiency.	
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Lower value.	Higher value.
							By calculation.	By Junkers calorimeter.				
	Brit. T.U. per lb.	Per cent.	Per cent.	Lbs.	Brit. T.U.	Per cent. by volume.	Brit. T.U. per cubic foot.		Cubic feet.	Brit. T.U.	Per cent.	Per cent.
Whole run—cold start.	14,319	3·37	3·975	241·37	3,456,000	H 15·2 CH_4 1·2 CO 21·0 CO_2 8·2 O 0·2 N 54·2	137·7	139·7	18,785	2,587,000	70	**75**
Last six hours—hot start.	14,319	3·37	3·975	158·60	2,271,000	H 15·60 CH_4 1·21 CO 21·05 CO_2 8·41 O 0·20 N 53·53	139·2	139·7	13,522	1,882,000	77	**83**

TABLE XXVI.—TRIAL OF 40 B.H.P. SUCTION PLANT WITH ANTHRACITE.

	FUEL.					GAS.					Heat efficiency.	
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Lower value.	Higher value.
							By calculation.	By Junkers calorimeter.				
	Brit. T.U. per lb.	Per cent.	Per cent.	Lbs.	Brit. T.U.	Per cent. by volume.	Brit. T.U. per cubic foot.		Cubic feet.	Brit. T.U.	Per cent.	Per cent.
Whole run—cold start.	13,887	3·60	8·76	245·25	3,406,000	H 15·59 CH 1·31 CO 19·05 CO_2 5·93 O 0·79 N 57·33	132·6	—	21,890	2,903,000	79	**85**
Last six hours—hot start.	13,887	3·60	8·76	180·00	2,500,000	H 15·64 CH_4 1·16 CO 20·13 CO_2 6·09 O 0·74 N 56·24	135·3	—	16,715	2,261,000	84	**90**

TABLE XXVII.—TRIAL OF 40 B.H.P. SUCTION PLANT WORKING WITH COKE.

	FUEL.					GAS.					Heat efficiency.	
	Calorific value by bomb calorimeter.	Moisture.	Ash and clinker.	Quantity of fuel burnt.	Total heat in fuel burnt.	Analysis—mean composition.	Calorific value.		Total gas generated, dry, at 0° C. and 760 mm.	Total heat in gas generated.	Lower value.	Higher value.
							By calculation.	By Junkers calorimeter.				
	Brit. T.U. per lb.	Per cent.	Per cent.	Lbs.	Brit. T.U.	Per cent. by volume.	Brit. T.U. per cubic foot.		Cubic feet.	Brit. T.U.	Per cent.	Per cent.
Whole run—cold start.	12,477	—	11·37	276·2	3,446,000	H 12·0 CH_4 0·4 CO 25·5 CO_2 5·3 O 0·65 N 56·15	133·3	133·6	21,786	2,903,700	80	84
Last six hours—hot start.	12,477	—	11·37	209·1	2,609,000	H 13·2 CH_4 0·35 CO 25·3 CO_2 5·4 O 0·6 N 55·15	136·2	136·9	17,053	2,322,500	84	89

APPENDIX B

1. Temperature.

Temperature is measured either on the Centigrade or on the Fahrenheit scale.

On the Centigrade scale, ice melts at 0° and water boils (under a pressure of 760 mm. of mercury) at 100°.

On the Fahrenheit scale, ice melts at 32° and water boils (under a pressure of 760 mm. of mercury) at 212°.

> To convert degrees Centigrade to Fahrenheit, multiply by 9, divide by 5, then add 32.
>
> To convert degrees Fahrenheit to Centigrade, subtract 32, then multiply by 5 and divide by 9.

The absolute temperature of a body is its temperature measured from the absolute zero ($-273°$ C. or $-459{\cdot}4°$ F.).

If the temperature of a body is $t°$ C., its absolute temperature is $t + 273$ Centigrade degrees.

If the temperature of a body is $t°$ F., its absolute temperature is $t + 459{\cdot}4$ Fahrenheit degrees.

The absolute temperature of melting ice is 273 Centigrade degrees, or 491·4 Fahrenheit degrees.

2. Heat Units.

The "calorie" is the quantity of heat required to raise the temperature of 1 kilo. of water through 1° C.

The "small calorie" is the quantity of heat required to raise the temperature of 1 gram of water through 1° C.

The "British thermal unit" (Brit. T.U.) is the quantity of heat required to raise the temperature of 1 lb. of water through 1° F.

$$\begin{aligned} 1 \text{ calorie} &= 1000 \text{ small calories.} \\ &= 3{\cdot}968 \text{ Brit. T.U.} \\ 1 \text{ Brit. T.U.} &= 0{\cdot}252 \text{ calorie.} \end{aligned}$$

3. Latent Heat of Steam.

The latent heat of steam at any temperature is the quantity of heat required to convert unit mass of water at that temperature into steam.

The latent heat of 1 kilo of steam at t° C. is (606·5 − 0·695 × t) calories.

The latent heat of 1 lb. of steam at t° F. is (1114 − 0·695 × t) Brit. T.U.

4. Specific Heat.

The specific heat of a substance is the quantity of heat required to raise the temperature of unit mass of it through 1 degree.

The specific heat of many substances is greater at high than at low temperatures.

The mean specific heat of a substance between any two temperatures t_1 and t_2 is the quantity of heat required to raise the temperature of unit mass of it from t_1 to t_2, divided by the range of temperature $(t_2 - t_1)$.

5. Maximum Pressure of Aqueous Vapour.

At a given temperature, water will evaporate until the pressure of its vapour above the surface of the liquid increases to a definite limit. Evaporation then ceases, and the space above the liquid water is said to be saturated with aqueous vapour. The maximum pressure of aqueous vapour depends solely on the temperature, and is not affected by the presence of gases or of other vapours in the same space.

Table XXVIII.—Pressure and Mass of Saturated Aqueous Vapour.

Temperature °C.	Pressure.		Mass.		Temperature °C.	Pressure.		Mass.	
	Millimeters of mercury.	Inches of mercury.	Grams per cubic meter.	Pounds per cubic foot.		Millimeters of mercury.	Inches of mercury.	Grams per cubic meter.	Pounds per cubic foot.
0	4·57	0·18	4·75	0·000297	10	9·14	0·36	9·22	0·000576
1	4·91	0·19	5·09	0·000317	11	9·77	0·38	9·83	0·000613
2	5·27	0·21	5·44	0·000340	12	10·43	0·41	10·47	0·000653
3	5·66	0·22	5·82	0·000364	13	11·14	0·44	11·14	0·000695
4	6·07	0·24	6·23	0·000389	14	11·88	0·47	11·85	0·000740
5	6·51	0·26	6·66	0·000416	15	12·67	0·50	12·61	0·000787
6	6·97	0·27	7·11	0·000444	16	13·51	0·53	13·40	0·000837
7	7·47	0·29	7·60	0·000474	17	14·39	0·57	14·24	0·000889
8	7·99	0·31	8·11	0·000506	18	15·33	0·60	15·12	0·000944
9	8·55	0·34	8·65	0·000540	19	16·32	0·64	16·05	0·001002

TABLE XXVIII.—*continued.*

Temperature °C.	Pressure.		Mass.		Temperature °C.	Pressure.		Mass.	
	Millimeters of mercury.	Inches of mercury.	Grams per cubic meter.	Pounds per cubic foot.		Millimeters of mercury.	Inches of mercury.	Grams per cubic meter.	Pounds per cubic foot.
20	17·36	0·63	17·03	0·001058	60	148 88	5·86	130·67	0·008139
21	18·47	0·73	18·06	0·001127	61	155·95	6·14	136·50	0·008521
22	19·63	0·77	19·14	0·001195	62	163·29	6·43	142·54	0·008896
23	20·86	0·82	20·29	0·001266	63	170·92	6·73	148·81	0·009313
24	22·15	0·87	21·49	0·001341	64	178·86	7·04	155·30	0·009695
25	23·52	0·93	22·75	0·001420	65	187·10	7·37	162·04	0·010115
26	24·96	0·98	24·07	0·001503	66	195·66	7·70	169·01	0 010550
27	26·47	1·04	25·46	0·001590	67	204·56	8·05	176·23	0·011001
28	28·06	1·10	26·92	0·001666	68	213·79	8·42	183·70	0·011467
29	29·74	1·17	28·45	0·001777	69	223·37	8·79	191·44	0·011951
30	31·51	1·24	30·06	0·001877	70	233·31	9·18	199·45	0·012737
31	33·37	1·31	31·74	0·001977	71	243·62	9·59	207·73	0·012967
32	35·32	1·39	33·51	0·002092	72	254·30	10·01	216·30	0·013503
33	37·37	1·47	35·36	0·002207	73	265·38	10·45	225·16	0·014056
34	39·52	1·56	37·29	0·002328	74	276·87	10·90	234·32	0·014627
35	41·78	1·65	39·32	0·002740	75	288·76	11·37	243·78	0·015218
36	44·16	1·74	41·44	0·002587	76	301·09	11·85	253·55	0·015828
37	46·65	1·84	43·65	0·002725	77	313 85	12·36	263·65	0·016459
38	49·26	1·94	45·97	0·002869	78	327·05	12·88	274·08	0·017110
39	52·00	2·05	48·38	0·003020	79	340·73	13·41	284·84	0·017782
40	54·86	2·16	50·91	0·003178	80	354·87	13·97	295·95	0·018475
41	57·87	2·28	53·55	0·003343	81	369·51	14·55	307·43	0·019192
42	61·02	2·40	56·30	0 003515	82	384·64	15·14	319·27	0·019930
43	64·31	2·53	59·18	0·003694	83	400·29	15·76	331·49	0·020694
44	67·76	2·66	62·18	0·003881	84	416·47	16·40	344·10	0·021481
45	71·36	2·81	65·30	0·004076	85	433·19	17·05	357·11	0·022293
46	75·13	2·96	68·56	0·004280	86	450·47	17·74	370·51	0·023130
47	79·07	3·11	71·95	0·004481	87	468·32	18·44	384·34	0·023993
48	83·19	3·28	75·48	0·004712	88	486·76	19·16	398·58	0·024882
49	87·49	3·44	79·16	0·004942	89	505·81	19·91	413·26	0·025799
50	91·98	3·62	82·99	0·005181	90	525·47	20·69	428·38	0·026742
51	96·66	3·81	86·97	0·005429	91	545·76	21·49	443·95	0·027714
52	101·55	4·00	91·12	0·005688	92	566·71	22·31	459·99	0·028715
53	106·65	4·19	95·43	0·005957	93	588·33	23·16	476·50	0·029746
54	111·97	4·40	99·91	0·006237	94	610·64	24·04	493·49	0·030807
55	117·52	4·63	104·56	0·006527	95	633·66	24·95	510·98	0·031899
56	123·29	4·85	109·40	0·006829	96	657·40	25·88	528·97	0·033045
57	129·31	5·09	114·42	0·007143	97	681·88	26·84	547·48	0·034177
58	135 57	5·34	119·61	0·007469	98	707·13	27·84	566·52	0·035365
59	142·10	5·59	125·05	0·007789	99	733·16	28·86	586·09	0·036587
					100	760·00	29·92	606·21	0·037843

6. The Laws of Gases.

(*a*) At a given temperature, the volume of a given mass of gas is inversely proportional to its pressure. (Boyle's Law.)

(*b*) At a given pressure, the volume of a given mass of gas is directly proportional to its absolute temperature. (Charles's Law.)

Hence if V_1 be the volume of a given mass of gas at pressure P_1 and absolute temperature T_1, and if V_0 be the volume which the gas would occupy at some other pressure P_0 and absolute temperature T_0, then—

$$\frac{P_1V_1}{T_1} = \frac{P_0V_0}{T_0}$$

and therefore—

$$V_0 = V_1 \times \frac{P_1}{P_0} \times \frac{T_0}{T_1}.$$

7. Reduction of the Volume of a Gas to the Standard Temperature and Pressure.

Unless otherwise stated, the volume of a gas means the volume it would occupy under the standard conditions of temperature and pressure, viz. 0° C. (32° F.) and 760 mm. (29·92 inches) of mercury.

If V_1 be the observed volume of the gas, measured at a temperature $t_1°$ C. and under a pressure P_1 mm. of mercury, the reduced volume (*i.e.* the volume which the gas would occupy at the standard temperature and pressure) is—

$$V_0 = V_1 \times \frac{P_1}{760} \times \frac{273}{t_1 + 273}.$$

If V_1 be the observed volume of the gas, measured at a temperature of $t_1°$ F. and under a pressure P_1 inches of mercury, the reduced volume is—

$$V_0 = V_1 \times \frac{P_1}{29{\cdot}92} \times \frac{491{\cdot}4}{t_1 + 459{\cdot}4}.$$

When a gas is measured over water (*e.g.* in a gasholder or by a wet meter) it is saturated with aqueous vapour. The actual pressure P_1 of the gas is the observed pressure minus the maximum pressure of aqueous vapour at the temperature of the gas.

8. Chemical Equations. Molecular Weights and Densities of Gases.

In a chemical equation the formulæ representing the different substances always refer to a quantity of the substance equal to its molecular weight in grams, kilos or pounds.

The molecular weight in grams of any gas occupies 22·32 liters, or the molecular weight in kilos occupies 22·32 cubic meters, or the molecular weight in pounds occupies 357·5 cubic feet, if measured at the standard temperature and pressure. This volume is called the "molecular volume" of a gas.

The chemical formula of a gas therefore always refers to the quantity of the gas which occupies 1 molecular volume at the standard temperature and pressure.

TABLE XXIX.—MOLECULAR WEIGHTS AND DENSITIES OF GASES.

Gas.	Formula.	Molecular weight.	Density.	
			Air = 1.	Weight of 1 liter in grams, or of 1 cubic meter in kilos.
Air	—	—	1·0000	1·2930
Carbon dioxide . .	CO_2	43·90	1·5197	1·9650
Carbon monoxide . .	CO	27·94	0·9671	1·2505
Ethylene	C_2H_4	27·95	0·9674	1·2509
Hydrogen	H_2	2·00	0·0692	0·0895
Methane	CH_4	15·97	0·5530	0·7150
Nitrogen	N_2	28·02	0·9701	1·2544
Oxygen	O_2	31·93	1·1052	1·4291
Water vapour . . .	H_2O	17·96	0·6218	0·8040

The following are the chemical equations representing the principal changes which occur in the formation and combustion of producer gas.

Formation of producer gas from air and carbon :—

$$C + O_2 = CO_2 + 97{,}600 \text{ calories.}$$
$$CO_2 + C = 2CO - 38{,}800 \quad ,,$$
$$2C + O_2 = 2CO + 58{,}800 \quad ,,$$

Reactions between steam and carbon :—

$$H_2O + C = H_2 + CO - 28{,}800 \text{ calories.}$$
$$2H_2O + C = 2H_2 + CO_2 - 18{,}800 \quad ,,$$

Reaction between steam and carbon monoxide :—

$$H_2O + CO = CO_2 + H_2 + 10{,}000 \text{ calories.}$$
$$CO_2 + H_2 = CO + H_2O - 10{,}000 \quad ,,$$

Combustion of the constituents of producer gas :—

$$2CO + O_2 = 2CO_2 + 136{,}400 \text{ calories.}$$
$$2H_2 + O_2 = 2H_2O + 138{,}000 \quad ,,$$
$$CH_4 + 2O_2 = CO_2 + 2H_2O + 213{,}500 \text{ calories.}$$
$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O + 341{,}100 \quad ,,$$

Example—

$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O + 341{,}100 \text{ calories.}$$

This equation tells us that 27·95 kilos of ethylene (see Table of Molecular Weights) combine with 3 × 31·93 or 95·79 kilos of oxygen to form 2 × 43·90 or 87·80 kilos of carbon dioxide and 2 × 17·96 or 35·92 kilos of water, and that 341,100 calories are evolved. The equation also tells us that 1 volume of ethylene requires for its combustion 3 volumes of oxygen, and that the products consist of 2 volumes of carbon dioxide and 2 volumes of steam (if the latter is not condensed).

9. Specific Heats of Gases.

The specific heat of a gas is greater when the gas is heated under a constant pressure (and therefore allowed to expand) than when it is heated at constant volume.

The difference between the specific heats of a gas at constant pressure and at constant volume is—

$$\frac{1\cdot98}{\text{molecular weight of the gas}} \text{ Centigrade units,}$$

or—

$$\frac{3\cdot564}{\text{molecular weight of the gas}} \text{ Fahrenheit units.}$$

TABLE XXX.—MEAN SPECIFIC HEATS OF GASES AT CONSTANT PRESSURE BETWEEN THE ABSOLUTE ZERO AND THE TEMPERATURE $t°$ C.[1]

Gas.	Mean specific heat (Centigrade units).
Carbon monoxide	$0{\cdot}2326 + 0{\cdot}0000214 \times (t + 273)$
Hydrogen	$3{\cdot}2500 + 0{\cdot}0003000 \times (t + 273)$
Methane	$0{\cdot}4070 + 0{\cdot}0000376 \times (t + 273)$
Nitrogen	$0{\cdot}2320 + 0{\cdot}0000214 \times (t + 273)$
Oxygen	$0{\cdot}2036 + 0{\cdot}0000188 \times (t + 273)$
Carbon dioxide	$0{\cdot}1481 + 0{\cdot}0000843 \times (t + 273)$
Water vapour	$0{\cdot}3619 + 0{\cdot}00001615 \times (t + 273)$

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[1] Based on Chatelier's values, "Cours de Chimie Industrielle."

The mean specific heat of a gas between any two temperatures $t_1°$ and $t_2°$ C. is found as follows :—

The mean specific heat between absolute zero and $t°$ C. is—

$$a + b(t + 273)$$

where the values of a and b are taken from Table XXX.

The heat required to raise the temperature of 1 kilo of the gas from the absolute zero to $t_1°$ C. is—

$$a(t_1 + 273) + b(t_1 + 273)^2 \text{ calories.}$$

The heat required to raise the temperature of 1 kilo of the gas from the absolute zero to $t_2°$ C. is—

$$a(t_2 + 273) + b(t_2 + 273)^2 \text{ calories.}$$

The heat required to raise the temperature of 1 kilo of the gas from $t_1°$ to $t_2°$ C. is the difference between these two quantities, or—

$$a(t_2 - t_1) + b(t_2 - t_1)(t_2 + t_1 + 546) \text{ calories.}$$

The mean specific heat between t_1 and t_2 is therefore—

$$a + b(t_2 + t_1 + 546).$$

Example.—The mean specific heat of carbon dioxide, at constant pressure, between 0° C. and 1000° C. is—

$$0{\cdot}1481 + 0{\cdot}0000843 \times 1546 = 0{\cdot}2784.$$

10. Molecular Heat of Gases.

The molecular heat of a gas is the quantity of heat required to raise the temperature of 22·32 cubic meters of the gas (or of its molecular weight in kilos) through 1° C.

TABLE XXXI.—MEAN MOLECULAR HEATS OF GASES AT CONSTANT PRESSURE BETWEEN THE ABSOLUTE ZERO AND THE TEMPERATURE $t°$ C.

ERRATUM

Page 270, Table XXX., last line:

for $0{\cdot}3619 + 0{\cdot}00001615 \times (t + 273)$

read $0{\cdot}3619 + 0{\cdot}0001615 \times (t + 273)$

Combustion of the constituents of producer gas :—

$$2CO + O_2 = 2CO_2 + 136{,}400 \text{ calories.}$$
$$2H_2 + O_2 = 2H_2O + 138{,}000 \quad ,,$$
$$CH_4 + 2O_2 = CO_2 + 2H_2O + 213{,}500 \text{ calories.}$$
$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O + 341{,}100 \quad ,,$$

Example—

$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O + 341{,}100 \text{ calories.}$$

This equation tells us that 27·95 kilos of ethylene (see Table of Molecular Weights) combine with 3 × 31·93 or 95·79 kilos of oxygen to form 2 × 43·90 or 87·80 kilos of carbon dioxide and 2 × 17·96 or 35·92 kilos of water, and that 341,100 calories are evolved. The equation also tells us that 1 volume of ethylene requires for its combustion 3 volumes of oxygen, and that the products consist of 2 volumes of carbon dioxide and 2 volumes of steam (if the latter is not condensed).

9. Specific Heats of Gases.

The specific heat of a gas is greater when the gas is heated under a constant pressure (and therefore allowed to expand) than when it is heated at constant volume.

The difference between the specific heats of a gas at constant pressure and at constant volume is—

$$\frac{1{\cdot}98}{\text{molecular weight of the gas}} \text{ Centigrade units,}$$

or—

$$\frac{3{\cdot}564}{\text{molecular weight of the gas}} \text{ Fahrenheit units.}$$

TABLE XXX.—MEAN SPECIFIC HEATS OF GASES AT CONSTANT PRESSURE BETWEEN THE ABSOLUTE ZERO AND THE TEMPERATURE t° C.[1]

The mean specific heat of a gas between any two temperatures $t_1°$ and $t_2°$ C. is found as follows :—

The mean specific heat between absolute zero and $t°$ C. is—

$$a + b(t + 273)$$

where the values of a and b are taken from Table XXX.

The heat required to raise the temperature of 1 kilo of the gas from the absolute zero to $t_1°$ C. is—

$$a(t_1 + 273) + b(t_1 + 273)^2 \text{ calories.}$$

The heat required to raise the temperature of 1 kilo of the gas from the absolute zero to $t_2°$ C. is—

$$a(t_2 + 273) + b(t_2 + 273)^2 \text{ calories.}$$

The heat required to raise the temperature of 1 kilo of the gas from $t_1°$ to $t_2°$ C. is the difference between these two quantities, or—

$$a(t_2 - t_1) + b(t_2 - t_1)(t_2 + t_1 + 546) \text{ calories.}$$

The mean specific heat between t_1 and t_2 is therefore—

$$a + b(t_2 + t_1 + 546).$$

Example.—The mean specific heat of carbon dioxide, at constant pressure, between 0° C. and 1000° C. is—

$$0{\cdot}1481 + 0{\cdot}0000843 \times 1546 = 0{\cdot}2784.$$

10. Molecular Heat of Gases.

The molecular heat of a gas is the quantity of heat required to raise the temperature of 22·32 cubic meters of the gas (or of its molecular weight in kilos) through 1° C.

TABLE XXXI.—MEAN MOLECULAR HEATS OF GASES AT CONSTANT PRESSURE BETWEEN THE ABSOLUTE ZERO AND THE TEMPERATURE $t°$ C.

Gas.	Mean molecular heat[1] (Centigrade units).
Carbon monoxide Hydrogen Methane Nitrogen Oxygen	$6{\cdot}5 + 0{\cdot}0006 \times (t + 273)$
Carbon dioxide	$6{\cdot}5 + 0{\cdot}0037 \times (t + 273)$
Water vapour	$6{\cdot}5 + 0{\cdot}0029 \times (t + 273)$

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[1] Le Chatelier, "Cours de Chimie Industrielle."

The mean molecular heat of a gas between any two temperatures t_1 and t_2 can be found from this table in the same way that the mean specific heat is found from Table XXX.

Example.—The mean molecular heat of carbon dioxide between 0° C. and 1000° C. is—

$$6·5 + 0·0037 \times 1546 = 12·22.$$

11. Calorific Power.

The calorific power of a substance is the quantity of heat given out by the combustion of unit mass (or of unit volume if the substance be a gas), the products of combustion being cooled to the temperature of the air.

1 calorie per kilo = 1·8 Brit. T.U. per pound.
1 Brit. T.U. per pound = 0·555 calorie per kilo.
1 calorie per cubic meter = 0·1124 Brit. T.U. per cubic foot.
1 Brit. T.U. per cubic foot = 8·900 calories per cubic meter.

TABLE XXXII.—CALORIFIC POWER OF GASES (BURNT AT CONSTANT PRESSURE).

Gas.	Calorific power.							
	Calories per kilo.		Brit. T.U. per pound.		Calories per cubic meter.		Brit T.U per cubic foot.	
	Higher value.	Lower value.[1]	Higher value.	Lower value.[1]	Higher value.	Lower value.[1]	Higher value.	Lower value.[1]
Carbon monoxide	2,436[2]	—	4,385	—	3,046	—	342·4	—
Ethylene . . .	12,182[2]	11,404	21,928	20,527	15,239	14,266	1713·0	1603·0
Hydrogen . . .	34,500[2]	29,050	62,100	52,290	3,088	2,601	347·1	292·3
Methane . . .	13,344[2]	11,981	24,019	21,566	9,541	8,567	1072·0	963·0
Carbon . . .	8,137·5[2]	—	14,647·5	—	—	—	—	—

If the combustion is accompanied by a change in volume, the calorific powers at constant pressure and at constant volume will be different.

Let n_1 be the number of molecular volumes (22·32 c.m.) of the gas together with the oxygen required for its combustion, and let n_2 be the number of molecular volumes of the products of combustion.

Then $n_1 - n_2$ is the change in volume, and the work done by or

---

[1] See Chap. XIV. p. 236.

[2] Berthelot, *Annales de Chimie et de Physique*, Series 5, Vol. XXIII., 1881; Series 6, Vol. XVIII., 1889; and Series 6, Vol. XXX., 1893.

against the pressure of the atmosphere is equivalent to $541 \times (n_1 - n_2)$ calories.

The nitrogen in the air used for combustion is also present in the products, and is therefore not taken into account.

If the volume of the products (at 0° C.) is less than the volume of the mixture of gas and oxygen, work is done by the pressure of the atmosphere when the gas is burnt at constant pressure, and the heat of combustion at constant pressure is greater than the heat of combustion at constant volume by $541 \times (n_1 - n_2)$ calories.

Example.—The combustion of 2 kilos (1 molecular volume) of hydrogen at constant pressure (760 mm. of mercury) gives 69,000 calories, the steam being condensed.

The oxygen required for the combustion is 0·5 molecular volume, and the volume of the products is zero. (The volume of the condensed water is negligible.)

Hence $n_1 = 1\cdot5$, $n_2 = 0$, and $(n_1 - n_2) = 1\cdot5$. The difference between the heats of combustion is therefore—

$$541 \times 1\cdot5 = 811 \text{ calories,}$$

and the "heat of combustion at constant volume" (steam condensed) is $69{,}000 - 811 = 68{,}189$ calories, for 2 kilos of hydrogen.

The gross calorific power of hydrogen at constant volume is therefore—

34,095 calories per kilo.

TABLE XXXIII.—CALORIFIC POWER OF GASES (BURNT AT CONSTANT VOLUME).

Gas.	Calorific power.							
	Calories per kilo.		Brit. T.U. per pound.		Calories per cubic meter.		Brit. T.U. per cubic foot.	
	Higher value.	Lower value.	Higher value.	Lower value.	Higher value.	Lower value.	Higher value.	Lower value.
Carbon monoxide	2,426	—	4,367	—	3,033	—	340·9	—
Ethylene . . .	12,143	11,365	21,858	20,457	15,191	14,218	1707·0	1597·0
Hydrogen . . .	34,095	28,645	61,371	51,561	3,052	2,565	343·0	288·2
Methane . . .	13,276	11,913	23,897	21,444	9,492	8,518	1067·0	958·0
Carbon . . .	8,137·5	—	14,647·5	—	—	—	—	—

In calculating the lower value of the calorific power, the change of volume during combustion is the same as for the higher value; the products of combustion are cooled to 0° C., so that at constant volume the steam is actually condensed, but the lower value of the calorific power is found by deducting the latent heat of the steam from the higher value, whether the gas is burnt at constant volume or at constant pressure.

The calorific power of a sample of producer gas may be readily found from its analysis by the aid of Table XXXIV.

TABLE XXXIV.—GROSS CALORIFIC POWER OF GAS AT CONSTANT PRESSURE, THE GAS BEING MEASURED DRY, AT 0° C. AND 760 MM. PRESSURE.

Calories per Cubic Meter.

Carbon monoxide (CO), per cent. by volume.	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
5	152	155	158	161	165	168	171	174	177	180
6	183	186	189	192	195	198	201	204	207	210
7	213	216	219	222	225	228	232	235	238	241
8	244	247	250	253	256	259	262	265	268	271
9	274	277	280	283	286	289	292	295	299	302
10	305	308	311	314	317	320	323	326	329	332
11	335	338	341	344	347	350	353	356	359	362
12	366	369	372	375	378	381	384	387	390	393
13	396	399	402	405	408	411	414	417	420	423
14	426	430	433	436	439	442	445	448	451	454
15	457	460	463	466	469	472	475	478	481	484
16	487	490	493	497	500	503	506	509	512	515
17	518	521	524	527	530	533	536	539	542	545
18	548	551	554	557	560	564	567	570	573	576
19	579	582	585	588	591	594	597	600	603	606
20	609	612	615	618	621	624	628	631	634	637
21	640	643	646	649	652	655	658	661	664	667
22	670	673	676	679	682	685	688	691	695	698
23	701	704	707	710	713	716	719	722	725	728
24	731	734	737	740	743	746	749	752	755	758
25	762	765	768	771	774	777	780	783	786	789
26	792	795	798	801	804	807	810	813	816	819
27	822	826	829	832	835	838	841	844	847	850
28	853	856	859	862	865	868	871	874	877	880
29	883	886	889	893	896	899	902	905	908	911

TABLE XXXIV. (*Calories per Cubic Meter*)—*continued.*

Hydrogen (H_2), per cent. by volume.	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
0	—	3	6	9	12	15	19	22	25	28
1	31	34	37	40	43	46	49	53	56	59
2	62	65	68	71	74	77	80	83	86	90
3	93	96	99	102	105	108	111	114	117	120
4	124	127	130	133	136	139	142	145	148	151
5	154	158	161	164	167	170	173	176	179	182
6	185	188	191	195	198	201	204	207	210	213
7	216	219	222	225	229	232	235	238	241	244
8	247	250	253	256	259	263	266	269	272	275
9	278	281	284	287	290	293	296	300	303	306
10	309	312	315	318	321	324	327	330	334	337
11	340	343	346	349	352	355	358	361	364	368
12	371	374	377	380	383	386	389	392	395	398
13	402	405	408	411	414	417	420	423	426	429
14	432	435	439	442	445	448	451	454	457	460
15	463	466	469	473	476	479	482	485	488	491
16	494	497	500	503	507	510	513	516	519	522
17	525	528	531	534	537	540	544	547	550	553
18	556	559	562	565	568	571	574	578	581	584
19	587	590	593	596	599	602	605	608	612	615
20	618	621	624	627	630	633	636	639	642	645
21	649	652	655	658	661	664	667	670	673	676
22	679	683	686	689	692	695	698	701	704	707
23	710	713	717	720	723	726	729	732	735	738
24	741	744	747	751	754	757	760	763	766	769
25	772	775	778	781	784	788	791	794	797	800
26	803	806	809	812	815	818	822	825	828	831
27	834	837	840	843	846	849	852	856	859	862
28	865	868	871	874	877	880	883	886	889	893
29	896	899	902	905	908	911	914	917	920	923

Methane (CH_4), per cent. by volume.	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9
0	—	10	19	29	38	48	57	67	76	86
1	95	105	114	124	133	143	152	162	172	181
2	191	200	210	219	229	238	248	257	267	277
3	286	296	305	315	325	334	344	353	363	372
4	382	391	401	410	420	429	439	448	458	468

Ethylene (C_2H_4), per cent. by volume.	0·0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0 8	0·9
0	—	15	30	46	61	76	92	107	122	137
1	152	168	183	198	213	229	244	259	274	290
2	305	320	335	351	366	381	396	412	427	442
3	457	472	487	502	517	533	548	563	578	594
4	609	624	639	655	670	685	700	716	732	747

Example—

	Composition of gas. Per cent. by volume.	Calorific Power (from Table XXXIV.). Calories per c.m.
Hydrogen	16·2	500
Carbon monoxide	21·0	640
Methane	1·3	124
Carbon dioxide	8·5	—
Oxygen	0·2	—
Nitrogen	52·8	—
Total	100·0	1264

The gross calorific power of the gas burnt at constant pressure is 1264 calories per cubic meter, or 142·0 Brit. T.U. per cubic foot.

The gross calorific power of the gas burnt at constant volume may be found from Table XXXIII.:—

Calorific Power.

Due to the hydrogen . . . $0{\cdot}162 \times 3052 = 494{\cdot}4$ calories

Due to the carbon monoxide $0{\cdot}210 \times 3033 = 636{\cdot}9$ „

Due to the methane . . . $0{\cdot}013 \times 9492 = 123{\cdot}4$ „

Total . . . 1254·7 calories per cubic meter.

or 141·0 Brit. T.U. per cubic foot.

Or it may be calculated from the gross calorific power at constant pressure, found as above, and the change in volume during combustion, as follows:—

Constituent.	Molecular volumes in 22·32 c.m. of the gas.	Molecular volumes of oxygen required for combustion.	Volume after combustion (molecular volumes).
Hydrogen	0·162	0·081	—
Carbon monoxide	0·210	0·105	0·210
Methane	0·013	0·026	0·013
Carbon dioxide	0·085	—	0·085
Oxygen	0·002	—	0·002
Nitrogen	0·528	—	0·528
Total	1·000	0·212	0·838

The contraction on combustion of 22·32 c.m. of the gas is therefore—

$$1{\cdot}212 - 0{\cdot}838 = 0{\cdot}374 \text{ molecular volumes.}$$

The difference between the calorific powers at constant pressure and constant volume is therefore—

$$\frac{0{\cdot}374}{22{\cdot}32} \times 541 = 9 \text{ calories per cubic meter.}$$

and the gross calorific power at constant volume is—

1264 − 9 = 1255 calories per cubic meter.

The nett calorific powers may be found from Tables XXXII. and XXXIII.:—

		Nett Calorific Power (constant pressure).
Due to the hydrogen . . .	0·162 × 2601 =	421·4 calories.
Due to the carbon monoxide	0·210 × 3046 =	639·7 ,,
Due to the methane . . .	0·013 × 8567 =	111·4 ,,
	Total . . .	1172·5 calories per cubic meter.

or 131·7 Brit. T.U. per cubic foot.

		Nett Calorific Power (constant volume).
Due to the hydrogen . . .	0·162 × 2565 =	415·5 calories.
Due to the carbon monoxide	0·210 × 3033 =	636·9 ,,
Due to the methane . . .	0·013 × 8518 =	110·8 ,,
	Total . . .	1163·2 calories per cubic meter.

or 130·7 Brit. T.U. per cubic foot.

The nett calorific powers may also be calculated by deducting the latent heat of the steam in the products from the corresponding gross calorific powers, as explained in Chapter XIV. (p. 251).

12. Calorific Intensity.

The calorific intensity or theoretical flame temperature of a substance is the temperature to which the products of combustion would be raised if the initial temperature were 0° C. or 32° F., assuming that the combustion is complete, that no excess of air or oxygen is used, and that all the heat evolved during the combustion of the substance is taken up by the products.

The actual flame temperature is always lower than the calculated value because none of these conditions are realised in practice.

In calculating the calorific intensity it is usually assumed that the specific heat of the products of combustion is the same at high as at low temperatures. The calorific intensity is then equal to—

$$\frac{\text{Calorific power}}{\text{Specific heat of products} \times \text{Mass of products from the combustion of unit mass.}}$$

The values obtained in this way are much higher than the observed flame temperatures, and it is better to take into account the increase of specific heat with temperature. This may be done with the help of Tables XXXV. and XXXVI., which show the number of calories required to raise the temperature of 22·32 liters of various gases from 0° C. to various temperatures, under constant pressure and under constant volume respectively.

Table XXXV.—Calories required to heat 22·32 Liters of Various Gases from 0° C. to Various Temperatures, under Constant Pressure.[1]

Temperature.	Oxygen, nitrogen, carbon monoxide or hydrogen.	Steam.	Carbon dioxide.
100° C.	0·68	0·83	0·87
200	1·39	1·73	1·85
300	2·10	2·67	2·87
400	2·82	3·69	3·99
500	3·56	4·76	5·17
600	4·31	5·89	6·44
700	5·07	7·07	7·77
800	5·85	8·30	9·16
900	6·63	9·62	10·66
1000	7·43	10·98	12·22
1100	8·24	12·40	13·85
1200	9·05	13·87	15·55
1300	9·89	15·41	17·33
1400	10·73	17·00	19·18
1500	11·59	18·65	21·11
1600	12·46	20·35	23·09
1700	13·34	22·13	25·18
1800	14·23	23·93	27·31
1900	15·14	25·83	29·55
2000	16·05	27·76	31·83
2100	16·98	29·74	34·18
2200	17·92	31·81	36·64
2300	18·87	33·91	39·14
2400	19·84	36·10	41·75
2500	20·81	38·32	44·40
2600	21·80	40·62	47·16
2700	22·80	42·95	49·96
2800	23·82	45·37	52·87
2900	24·84	47·82	55·81
3000	25·88	50·35	58·86

---

[1] Based on the values given in Table XXXI. Mahler, *Revue Universelle des Mines*, 1904, vol. v. p. 8.

Table XXXVI.—Calories required to heat 22·32 Liters of Various Gases from 0° C. to Various Temperatures, under Constant Volume.[1]

Temperature.	Oxygen, nitrogen, carbon monoxide or hydrogen.	Water vapour.	Carbon dioxide.
100° C.	0·48	0·63	0·67
200	0·99	1·33	1·45
300	1·51	2·08	2·28
400	2·03	2·90	3·20
500	2·57	3·77	4·18
600	3·12	4·70	5·25
700	3·68	5·68	6·38
800	4·27	6·72	7·58
900	4·85	7·84	8·88
1000	5·45	9·00	10·24
1100	6·06	10·22	11·67
1200	6·67	11·49	13·17
1300	7·32	12·84	14·76
1400	7·96	14·23	16·41
1500	8·62	15·68	18·14
1600	9·29	17·18	19·92
1700	9·97	18·76	21·81
1800	10·67	20·37	23·75
1900	11·38	22·07	25·79
2000	12·09	23·80	27·87
2100	12·82	25·58	30·02
2200	13·56	27·45	32·28
2300	14·32	29·36	34·59
2400	15·09	31·35	37·00
2500	15·86	33·37	39·45
2600	16·65	35·47	42·01
2700	17·45	37·60	44·61
2800	18·28	39·83	47·33
2900	19·10	42·08	50·07
3000	19·94	54·41	52·92

Examples—

(*a*) Calorific intensity of hydrogen, when burnt in air, at constant pressure.

The combustion takes place according to the equation—

$$2H_2 + O_2 = 2H_2O + 2 \times 58,200 \text{ calories.}$$

The combustion of 2 grams of hydrogen therefore requires $\frac{1}{2} \times 22·32$ liters of oxygen, and 58·2 calories are evolved.

The products of combustion consist of 22·32 liters of water vapour, mixed with $\frac{1}{2} \times 3·76 \times 22·32$ or $1·88 \times 22·32$ liters of nitrogen (see p. 6).

---

[1] Based on the values given in Table XXXV.

To raise the temperature of the products from 0° C. to 2000° C. at constant pressure requires, according to Table XXXV.—

For the water vapour	1 × 27·76 = 27·76	calories.
For the nitrogen	1·88 × 16·05 = 30 17	„
Total . . .	57·93	„

To raise the temperature of the products from 0° C. to 2100° C. at constant pressure requires—

For the water vapour	1 × 29·74 = 29·74	calories.
For the nitrogen	1·88 × 16·98 = 31·92	„
Total . . .	61·66	„

The quantity of heat available for heating the products is 58·2 calories, and the calorific intensity is therefore between 2000° C. and 2100° C. The excess above 2000° C. is approximately—

$$100 \times \frac{58{\cdot}20 - 57{\cdot}93}{61{\cdot}66 - 57{\cdot}93} = 7^\circ \text{ C.}$$

The calorific intensity of hydrogen in air at constant pressure is therefore 2007° C. or 3645° F.

(*b*) Calorific intensity of carbon monoxide, when burnt in air, at constant pressure.

The combustion takes place according to the equation—

$$2CO + O_2 = 2CO_2 + 136{,}400 \text{ calories.}$$

The combustion of 28 grams of carbon monoxide therefore requires $\frac{1}{2} \times 22{\cdot}32$ liters of oxygen, and 68·2 calories are evolved.

The products of combustion consist of 22·32 liters of carbon dioxide and 1·88 × 22·32 liters of nitrogen.

To raise the temperature of the products from 0° C. to 2100° C. at constant pressure requires—

For the carbon dioxide	1 × 34·18 = 34·18	calories.
For the nitrogen	1·88 × 16·98 = 31·92	„
Total . . .	66·10	„

To raise the temperature of the products from 0° C. to 2200° C. at constant pressure requires—

For the carbon dioxide	1 × 36·64 = 36·64	calories.
For the nitrogen	1·88 × 17·92 = 33·69	„
Total . . .	70 33	„

The calorific intensity exceeds 2100° C. by—

$$100 \times \frac{68{\cdot}20 - 66{\cdot}10}{70{\cdot}33 - 66{\cdot}10} = 50^\circ \text{ C.}$$

The calorific intensity of carbon monoxide in air at constant pressure is therefore 2150° C. or 3900° F.

(*c*) Calorific intensity of a sample of producer gas when burnt in air at constant pressure.

	Composition of gas. Per cent. by volume.
Hydrogen	16·2
Carbon monoxide	21·0
Methane	1·3
Carbon dioxide	8·5
Oxygen	0·2
Nitrogen	52·8
Total	100·0

The nett calorific power of the gas at constant pressure is 1172·5 calories per c.m. (see p. 269), and the heat of combustion of 22·32 liters is 1172·5 × 0·02232 = 26·17 calories.

(The nett calorific power is taken because the steam in the products of combustion is not condensed.)

The products of combustion of 22·32 liters of the gas consist of:—

Water vapour—

0·162 × 22·32 liters due to the hydrogen.
0·026 × 22·32 liters due to the methane.

Total . 0·188 × 22·32 liters.

Carbon dioxide—

0·210 × 22·32 liters due to the carbon monoxide.
0·013 × 22·32 liters due to the methane.
0·085 × 22·32 liters present in the producer gas.

Total . 0·308 × 22·32 liters.

Nitrogen—

The oxygen required for combustion is:—

0·081 × 22·32 liters for the hydrogen.
0·105 × 22·32 liters for the carbon monoxide.
0·026 × 22·32 liters for the methane.

0·212 × 22·32 liters.
Less . 0·002 × 22·32 liters present in the producer gas.

Total . 0·210 × 22·32 liters.

The nitrogen in the air used for combustion is therefore—

0·210 × 22·32 × 3·76 = 0·790 × 22·32 liters.

and the nitrogen present in the gas is	0·528 × 22·32	,,
Total . . .	1·318 × 22·32	,,

To raise the temperature of the products from 0° C. to 1500° C. at constant pressure requires—

For the water vapour	0·188 × 18·65 =	3·51	calories.
For the carbon dioxide	0·308 × 21·11 =	6·50	,,
For the nitrogen	1·318 × 11·59 =	15 28	,,
	Total . . .	25·29	,,

To raise the temperature of the products from 0° C. to 1600° C. at constant pressure requires—

For the water vapour	0·188 × 20·35 =	3·83	calories.
For the carbon dioxide	0·308 × 23·09 =	7·11	,,
For the nitrogen	1·318 × 12·46 =	16·42	,,
	Total . . .	27·36	,,

The calorific intensity exceeds 1500° C. by—

$$100 \times \frac{26{\cdot}17 - 25{\cdot}29}{27{\cdot}36 - 25{\cdot}29} = 42^\circ \text{ C.}$$

and the calorific intensity of the gas when burnt in air at constant pressure is 1542° C. or 2808° F.

(*d*) Calorific intensity of a sample of producer gas when burnt in air at constant volume.

For the same sample of gas the nett calorific power at constant volume is 1163·2 calories per cubic meter (see p. 269), and the heat of combustion of 22·32 liters is 1163·2 × 0·02232 = 25·96 calories.

To raise the temperature of the products from 0° C. to 1800° C. at constant volume requires—

For the steam	0·188 × 20·37 =	3·83	calories.
For the carbon dioxide	0·308 × 23·75 =	7·32	,,
For the nitrogen	1·318 × 10·67 =	14·06	,,
	Total . . .	25·21	,,

To raise the temperature of the products from 0° C. to 1900° C. at constant volume requires –

For the steam	0·188 × 22·07 =	4·15 calories.
For the carbon dioxide	0·308 × 25·79 =	7·94 „
For the nitrogen	1·318 × 11·38 =	15·00 „
	Total . . .	27·09 „

The calorific intensity exceeds 1800° C. by—

$$100 \times \frac{25{\cdot}96 - 25{\cdot}21}{27{\cdot}09 - 25{\cdot}21} = 40^\circ \text{ C.}$$

and the calorific intensity of the gas when burnt in air at constant volume is 1840° C. or 3344° F.

It is interesting to note that the theoretical flame temperature is considerably higher (nearly 300° C.) when the combustion takes place at constant volume than when the gas is burnt at constant pressure.

13. Metric Equivalents.

Length.

1 meter = 39·37 inches.
1 meter = 3·281 feet.

1 inch = 25·4 millimeters.
1 foot = 304·8 „

Surface.

1 sq. meter = 1550·06 sq. ins.
1 sq. meter = 10·7643 sq. feet.

1 square inch = 6·45 sq. cms.
1 square foot = 929·0 „

Volume.

1 cub. cm. = 0·061 cubic in.
1 cub. meter = 35·317 cubic ft.
1 liter = 0·2201 gallon.

1 cubic inch = 16·4 cub. cms.
1 cubic foot = 0·028315 c.m.
1 gallon = 4·543 liters.

Weight.

1 kilo = 2·2046 lbs.
1000 kilos (1 metric ton) = 2204·6 lbs.

1 lb. = 453·59 grams.
1 ton (British) = 1016·05 kilos.

Pressure.

1 kilo per sq. cm. = 14·22 lbs. per sq. in.

1 lb. per sq. in. = 0·07032 kilo per sq. cm.

14. General Data.

One liter of water (at its greatest density) weighs 1 kilo.

One cubic meter or 1000 liters of water (at its greatest density) weighs 1000 kilos or 1 metric ton.

1 lb. per sq. in. = 27·65 inches water column.
= 2·035 inches mercury column.
1 in. water column = 0·0736 inch mercury column.
1 Brit. T.U. = 778 foot pounds.
1 Calorie = 42·7 kilogram-meters.
1 B.H.P.-hour = 641·4 calories.
= 2545 Brit. T.U.
1 Electrical H.P.-hour (Board of Trade Unit) = 1 kilowatt-hour.
= 1·34 B.H.P-hours.

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