No. 13. **GASES MET WITH IN COAL MINES.** By J. J. Atkinson. Third edition, revised and enlarged, to which is added The Action of Coal Dusts by Edward H. Williams, Jr.

No. 14. **FRICTION OF AIR IN MINES.** By J. J. Atkinson. Second American edition.

No. 15. **SKEW ARCHES.** By Prof. E. W. Hyde, C.E. Illustrated. Second edition.

No. 16. **GRAPHIC METHOD FOR SOLVING** Certain Questions in Arithmetic or Algebra. By Prof. G. L. Vose. Third edition.

*No. 17. **WATER AND WATER-SUPPLY.** By Prof. W. H. Corfield, of the University College, London. Second American edition.

No. 18. **SEWERAGE AND SEWAGE PURIFI**cation. By M. N. Baker, Associate Editor "Engineering News." Fifth edition, revised and enlarged.

No. 19. **STRENGTH OF BEAMS UNDER** Transverse Loads. By Prof. W. Allan, author of "Theory of Arches." Second edition, revised.

No. 20. **BRIDGE AND TUNNEL CENTRES.** By John B. McMaster, C.E. Second edition.

No. 21. **SAFETY VALVES.** By Richard H. Buel, C.E. Third edition.

No. 22. **HIGH MASONRY DAMS.** By E. Sherman Gould, M. Am. Soc. C.E. Second edition.

No. 23. **THE FATIGUE OF METALS UNDER** Repeated Strains. With various Tables of Results and Experiments. From the German of Prof. Ludwig Spangenburg, with a Preface by S. H. Shreve, A.M.

No. 24. **A PRACTICAL TREATISE ON THE** Teeth of Wheels. By Prof. S. W. Robinson. Third edition, revised, with additions.

No. 25. **THEORY AND CALCULATION OF** Cantilever Bridges. By R. M. Wilcox.

No. 26. **PRACTICAL TREATISE ON THE PROP**erties of Continuous Bridges. By Charles Bender, C.E.

No. 27. **BOILER INCRUSTATION AND CORRO**sion. By F. J. Rowan. New edition. Revised and partly rewritten by F. E. Idell.

*No. 28. **TRANSMISSION OF POWER BY WIRE** Ropes. By Albert W. Stahl, U.S.N. Fourth edition, revised.

No. 29. **STEAM INJECTORS; THEIR THEORY** and Use. Translated from the French by M. Leon Pochet.

ELEMENTS

OF

GAS ENGINE DESIGN,

BY

SANFORD A. MOSS, M.S., PH. D.

Mem. Am. Soc. Mechanical Engineers, Engineer, General Electric Co., Formerly Instructor in Machine Design, Cornell University.

Reprint of a Set of Notes accompanying a Course of Lectures delivered at Cornell University in 1902, and of Articles from "American Machinist," "Machinery" and "Power."

WITH ADDITIONS.

SECOND EDITION.

NEW YORK:

D. VAN NOSTRAND COMPANY,

23 Murray and 27 Warren Sts.,

1907

PREFACE.

This work is an attempt to present, in a condensed form, all of the fundamental principles with which a designer of gas engines should be familiar. A complete exposition of the elements only of all subjects of direct interest to the designer is aimed at.

No attempt is made to go into mathematical or constructional details, as this is manifestly impossible in a work of this size.

In Chapters I to V is given a general outline of the physics and chemistry of the gas engine and a discussion of gas engine fuels, leading up to Table 3 which gives the relative power yielded by various fuels in a given engine. Chapters VI to IX give a discussion of the action in a gas engine cylinder, from the designer's point of view, leading up to Chapter X, which gives the method of finding the size of cylinder for a given power.

Chapters XI to XIII briefly outline the more important principles of gas engine construction, leading up to Chapter XIV which gives rational formulas for most parts of a gas engine, with constants derived directly from modern American practice, all conveniently arranged for the designer's use.

The reader is assumed to be familiar with the general features of the gas engine and its operation. Most of the work treats of the *Otto* cycle or *four stroke* cycle gas engine, and, if not stated to the contrary, *each discussion is supposed to apply primarily to a single acting trunk piston engine using this cycle.* In some cases a discussion obviously applies to other cases also. Some features of other cases not common with the Otto cycle are also discussed briefly.

CONTENTS.

CHAPTER I.

Chemistry and Physics of Gas Engines.

Heat Engines.—The gas engine is a particular form of what is called a heat engine. A "heat engine" is an apparatus for converting the potential energy of chemical combination, first into heat energy and then into mechanical energy. In brief, a heat engine yields power from fuels. In most heat engines the heat is obtained from the chemical combination or "combustion" of a substance called "fuel" with the oxygen of the air. This heat is applied to increase the volume or pressure of some gas called the "working substance." The pressure is applied to a piston, and from this piston mechanical power is taken by appropriate means.

Steam and Air Engines.—In steam engines the heat of combustion is applied to increase the temperature of the gaseous products resulting from the combustion. These high temperature gases transfer their heat to the working substance, water and steam, through the walls of a boiler, and the steam is used to do work upon the engine piston. In air engines the products of combustion transfer their heat to a mass of air which forms a working substance, through the walls of some containing vessel.

Internal Combustion Engine.—We shall find that it is not necessary to transfer the heat of combustion from the products of combustion to the working substance used in the engine, but that the fuel and products of combustion may themselves be used as the working substance. In this case the fuel, reduced to a gas, and the air necessary for its combustion, are used as a working substance for the preliminary operations of the cycle. At the proper time heat is added to this working substance, not by transfer from some other hot body but by its own combustion. The cycle is then completed with the products of combustion. These products usually occupy about the same volume at any given temperature, before combustion and afterward, so that we need consider only the change of temperature and the corresponding changes of pressure, etc. That is to say, we suppose a certain amount of heat is added to our original working substance, without regard to the way in which the heat was obtained or the changes in the chemical composition of the working substance due to combustion.

Thus the method of adding heat is not material so far as the abstract thermodynamic cycle is concerned, but is very important in determining the form of engine to carry out the cycle.

A heat engine in which heat is added to the working substance by its own combustion is called an "internal combustion engine," or more briefly a "gas engine."

Combustibles.—"Combustion" is a chemical combination of two substances which evolves heat. The combining substances are called "combustibles." In all of the cases we shall deal with, one of the combustibles is the oxygen of the air, and the other is some form of hydrogen and carbon compound, and is called "fuel."

The compound, carbon monoxide or carbonic oxide, CO., is a fuel, as is also pure hydrogen, H_2. All the other fuels we are concerned with are compounds of hydrogen and carbon called "hydro-carbons." These occur in groups, the members of each group forming what is called a "homologous series."

The most important is the group of "paraffin." The members of this group having the least density are as follows:—

PARAFFINS.

Methane (Marsh gas or fire damp)	CH_4
Ethane (Gas at ordinary temperatures)	C_2H_6
Propane (Gas at ordinary temperatures)...	C_3H_8
Butane (Boils at 34)	C_4H_{10}
Pentane (Boils at 100)	C_5H_{12}
Hexane (Boils at 158)................	C_6H_{14}

There are many other members of the series which are not important. The general formula is $C_nH_{2n}+_2$. By assigning different values to *n* the formula of any member is obtained. Thus, for Methane *n* is 1, for Ethane it is 2, etc. Crude petroleum is composed principally of paraffins. The paraffins are called "saturated hydrocarbons." All of the other hydrocarbons we shall consider are called "unsaturated hydrocarbons."

The most important of these is the group of "olefins." The first three members are given below. They are gases and occur in illuminating gas.

OLEFINS.

Ethylene (Olefiant Gas).............	C_2H_4
Propylene..............................	C_3H_6
Butylene...............................	C_4H_8

The Acetylene Group has the formula $C_n H_{2n-2}$ and the only important member is acetylene Gas, $C_2 H_2$.

The "Benzene Group" has a general formula $C_n H_{2n-6}$ and the principal member is benzene, $C_6 H_6$. This is a liquid, boiling at 176°. Benzene vapor is found in coal gas.

There are many more complicated hydrocarbons, among which may be mentioned Naphthalene, $C_{10} H_8$ which, with allied substances, compose "coal tar."

Sulphur, iron and many other substances burn in oxygen, but are not usually considered as fuels.

Reactions of Combustion.—When a fuel and oxygen combine, the carbon present goes to form carbonic acid gas, or carbon dioxide, CO_2, while the hydrogen present goes to form water, H_2O, usually in the shape of superheated steam. Typical reactions are as follows:—

REACTIONS OF COMBUSTION.

$$2H_2+O_2=2H_2O \qquad (1)$$
$$2CO+O_2=2CO_2 \qquad (2)$$
$$C+O_2=CO_2 \qquad (3)$$
$$CH_4+2O_2=CO_2+2H_2O \qquad (4)$$
$$C_2H_4+3O_2=2CO_2+2H_2O \qquad (5)$$
$$2C_2H_2+5O_2=4CO_2+2H_2O \qquad (6)$$

As we shall see later, these reactions do not occur until the substances are heated sufficiently.

Decomposition.—In order that the reactions of the preceding article may occur, a sufficient amount of oxygen must of course be present.

If a hydrocarbon is heated and there be no oxygen to combine with it, decomposition takes place, the hydrocarbon splitting up into other hydrocarbons.

The exact circumstances under which the various hydrocarbons are decomposed are not very well understood. In a general way the following effects occur, although circumstances may modify them greatly.

Heat decomposes paraffins into olefins, olefins and benzine into acetylene, and acetylene into carbon and naphthalene and other tarry substances. At very high temperatures water and carbon dioxide are decomposed. This action probably never takes place at any temperature with which we are concerned.

However, carbon at moderately high temperatures will decompose carbon dioxide, forming carbon monoxide. Hot carbon will also decompose water, forming hydrogen and carbon monoxide.

Heat of Combustion.—When reactions of combustion occur a quantity of heat is liberated which goes to increase the temperature of the products of combustion. This heat is usually measured by means of a "Constant Pressure Calorimeter," the most usual form being "Junker's Calorimeter." The combustibles are burned at atmospheric pressure in a vessel surrounded by a large quantity of water, and the products of combustion led through a coil also surrounded by the water, until their temperature is reduced to that of the water. Any water formed by the combustion is condensed, and the latent heat is also given up to calorimeter. Corrections are made to bring the products of combustion, combustibles and the condensed water to 32° F. The "heat of combustion" may therefore be defined as the amount of heat liberated by combustion at atmospheric pressure, the combustibles being initially at 32° F. and the products of combustion reduced to the same temperature, all the water of combustion being condensed.

Higher and Lower Heating Values.—The heat of combustion as thus defined is called the "higher heating value" and includes the amount of sensible heat actually added to the products of combustion, as well as an amount of latent heat which exists as potential energy in the steam formed.

That is to say, only a portion of the total calorimetric heat of combustion, called the "lower heating value," is liberated by the chemical reaction and goes to heat the products of combustion. The other portion is due to the difference between the amount of heat required to heat the combustibles from 32° to the ignition point and the amount of heat liberated when the products of combustion are cooled from the ignition point to 32°. If the combustibles are all gaseous, this latter amount of heat is greater than the former by the latent heat of condensation of the water, and the difference between the heat of the water from 32° to 212° and the heat of the same weight of gas between the same limits. This is due to the fact that the specific heats of the combustibles and products of combustion are nearly equal so long as both are gaseous. That is to say, the measured heat of combustion, if the combustibles and products of combustion, are brought to the same temperature, will be the same for all temperatures over 212°.

If the fuel supplied to the engine is

liquid, appropriate corrections should be made for the latent heat of the oil. This is small and is often omitted.

The total heat of water at 212°, including the heat of the liquid from 32° and the latent heat, is 1146.6 B. T. U. The heat required to raise an equal weight of combustible gases through the same range is $180 \times .238 = 42.8$. The difference, 1104 B. T. U. per pound of water formed, is that part of the higher heating value not obtained by the direct combustion, and is to be subtracted from it in order to obtain the lower heating value for a gaseous fuel. This is equivalent to deducting 9870 B. T. U. per lb. of hydrogen present. Sometimes the higher heating value is given for the water condensed at 60°, or various other assumptions are made, and then the correction for the lower value varies accordingly.

The gas engine itself is responsible only for the lower heating value, and we will use it in all efficiency and other calculations. This whole matter is a subject of dispute at present, however.

Table 1 gives values of the Heat of Combustion of Elementary Gases, and Table 2 gives a scheme for computing the Heat of Combustion for a mixture from the values of Table 1. The heating value of a mechanical mixture of several gases is, of course, the sum of the separate heating values. This does not apply to a chemical mixture however. That is, the heating value of a hydrocarbon is not the sum of the heating values of carbon and hydrogen contained. Note that the analysis of a gas is almost always by volume.

Ignition.—When a mixture composed of oxygen and some gaseous fuel is brought to the "ignition" temperature, the chemical combination, called "combustion," occurs. The ignition temperature varies greatly for different substances. The exact values are not very well known. It is probable that with most hydrocarbons the ignition temperature increases as the boiling point and the molecular weight decrease. Thus the lightest paraffins and olefins have the greatest ignition temperatures, and the light paraffins higher ignition temperatures than the light olefins. Hydrogen ranks about with ethylene. Carbon monoxide ignites at a greater temperature than any of the hydrocarbons.

There is usually no difficulty in heating a small portion of a mass of gas to the ignition point by a red hot surface or an electric spark.

Sometimes there is a difficulty in the other direction, that is in preventing ignition. When a charge is compressed it becomes heated, and often the ignition temperature is reached before the proper time, and "premature ignition" occurs, as we will see later.

The temperature of ignition is always higher than the boiling point of a substance, so that vaporization always takes place before ignition. That is to say, a substance must always be vaporized before it will ignite. There may be exceptions to this rule but it holds for all our cases.

Inflammation.—When any small portion of a combustible mass is heated to the ignition point it burns, and its heat of combustion heats the neighboring portion of the mass. This process, whereby ignition is spread throughout the mass, is termed "inflammation."

Velocity of Flame Propagation.—The rate at which inflammation proceeds is termed the "velocity of flame propagation."

The greater the original temperature of the mixture the less the time required to bring successive uninflamed layers to the ignition point, and hence the greater the flame velocity.

The greater the amount of heat to be added to obtain the ignition temperature the less will be the flame velocity. Thus a mixture of unvaporized oil spray and air will burn rather slowly, because the oil must first be vaporized. This requires the addition of the latent heat of vaporization.

Any cooling action will decrease the velocity of inflammation, as for instance cool cylinder walls surrounding a mass of gas.

Sometimes a mass conducts heat away so rapidly that a considerable amount of heat must be applied in order to start inflammation. Thus a tank of kerosene oil cannot be lighted by a small flame, as the heat is conducted away so rapidly that the ignition point is not reached by enough of the oil to cause inflammation to begin. When a large part of the mass is initially ignited the flame starts from a number of places at once and therefore spreads through the entire mass with a great rapidity. This effect is sometimes produced by having an ignition flame which shoots straight out for some distance into the mass to be ignited.

The same effect is produced when an explosive which can be ignited by concussion is subjected to such a shock that it ignites in several places at once. The entire mass then becomes inflamed with extraordinary rapidity.

The ignition temperature is supposed by some to be decreased by increase of pressure. If this is so, it accounts for the observed fact that flame spreads more rapidly when a mixture is compressed. However, the fact that the particles are closer together and that therefore heat is radiated from one to another more quickly, may also be the explanation. At any rate compression greatly increases the inflammability of a gaseous mixture.

Dilution.—When a fuel and oxygen are present in exact proportions to combine without leaving an excess of either, the mixture is said to be "perfect." When any inert gas is present, as nitrogen, carbonic acid from a previous combustion, or an excess of either combustible, the mixture is said to be "diluted." The most perfect mixture possible of a fuel and air, is of course diluted with nitrogen.

In a diluted mixture the heat of combustion of an inflamed layer must heat up a quantity of inert gas before the combustible portion of the next layer will ignite. Hence dilution reduces the velocity of flame propagation.

When the dilution is very great the flame will not spread at all, and the mixture is said to be "non-explosive."

There is a very considerable range between a perfect mixture and one so dilute as to be non-explosive. However, the exact value of the greatest possible dilution, under conditions present in a gas engine cylinder, is not accurately known.

Since compression increases the inflammability, a mixture which is too diluted to explode or burn at atmospheric pressure, will explode rapidly when compressed. Many gases too weak to burn in air are used in gas engines.

Often a diluted mixture is not uniform. That is, there are portions which are very dilute, and other portions where the mixture is nearly perfect. This usually causes a very slow average rate of flame propagation.

Practical Flame Velocities.—In most cases the subject of flame velocity requires no attention for gas engine purposes. The greatest piston speeds and largest cylinders in use do not seem to require efforts to increase flame velocity, if the mixtures are uniform.

CHAPTER II.

Gassification of Coal.

Composition of Coal.—Coal is a compound of carbon and various hydrocarbons together with incombustible matter called "ash," and small amounts of water, sulphur, etc. When a moderate amount of heat is applied, some of the hydrocarbons are vaporized and others decomposed into volatile hydrocarbons and free carbon. The hydrocarbons thus set free form what is termed "volatile matter." The balance of the combustible part of the coal is termed "fixed carbon" and can not be directly vaporized. "Bituminous" coal has more than, and "anthracite" less than 12% of volatile matter. Some bituminous coals have 50% of volatile matter, and some anthracite only 1 or 2%.

Coal Gas.—The most obvious way to obtain a combustible gas from coal is to heat it and use the volatile portion which is thereby liberated; in which case the fixed carbon is left as a residue. This was the first process used in obtaining a gas from coal and it is still in extensive use.

Of course only highly bituminous coal can be used, as the fixed carbon does not furnish any of the gas and only acts as an inert substance.

The coal is placed in a closed air tight "retort" and heated, perhaps to redness, and "distilled." The volatile matter is given off in various forms according to the kind of coal, temperature, time of heating, etc. The gas is then subjected to an extensive system of cleaning and purification, in order to remove dust, tar, ammonia, carbon dioxide, sulphur and other impurities.

The final result is a gas containing about 50% of hydrogen, 40% of methane, 5% of unsaturated hydrocarbons, such as ethylene and benzene, and 5% of carbon monoxide. There are also impurities, such as carbonic acid, nitrogen, etc.

Unsaturated Hydrocarbons in Coal Gas.—The illuminating power is found to depend almost wholly on the unsaturated hydrocarbons, and therefore the distillation of the coal is so conducted as to render these a maximum.

However, the heat of combustion of the gas does not depend to any marked degree on the particular composition of the hydrocarbons present. That is to say, the value of the gas for gas engine purposes does not depend on its value for illuminating purposes. A gas which contains less than the normal amount of unsaturated hydrocarbons would give a dull flame but might be a very good heating gas.

The gas is also purified to a much greater degree than would be necessary if it were to be used in gas engines only. For these reasons, therefore, coal gas manufactured for illuminating purposes is more expensive than need be for gas engine purposes.

When coal gas is analyzed, the unsaturated hydrocarbons are often not determined exactly. These hydrocarbons are all soluble in fuming sulphuric acid, and the volume thus absorbed is called "Heavy Hydrocarbons," or "Illuminants." When so given the hydrocarbons may be counted as wholly propylene in finding the total heat of combustion, density, etc.

Sometimes the unsaturated hydrocarbons are divided into two parts, by absorbing in alcohol and then in fuming sulphuric acid. The hydrocarbons absorbed by alcohol are often called "light hydrocarbons," and may be taken as being wholly benzene. The balance of the unsaturated hydrocarbons absorbed by fuming sulphuric acid are called "heavy hydrocarbons" and are mainly olefins. They may be taken as being wholly propylene.

By-products of Gas Manufacture.—When illuminating gas is manufactured as described, a number of by-products which are commercially valuable are obtained in addition to the gas itself. The fixed carbon of the coal is all left in the retorts after the volatile matter has passed off and is sold as "gas-coke." Sometimes the coke is not valuable enough for sale on account of local conditions, and it is then burned under the retorts.

The decomposition of the complex hydrocarbons leaves a deposit of nearly pure carbon on the retort walls, called "gas carbon." Other hydrocarbons are vaporized and pass off with the gas, but are condensed when the gas is cooled to atmospheric temperature. These form "coal tar," and from it many valuable chemical substances, dye stuffs, etc., are obtained. A quantity of ammonia is removed from the gas during its purification, and this finds ready sale.

Coke Oven Gas.—When coal is distilled to make illuminating gas, the coke is a by-product. However, coke is in such demand that coal is often distilled to make coke, and gas is a by-product. Originally this was done in "bee hive ovens," and all of the gas was burned in order to furnish the heat to distil or "carbonize" the coal. Recently more economical coke ovens have been introduced, one being the "Sennett-Solvay" coke oven, exploited by the Solvay Co. of Syracuse.

These ovens give off a gas exactly similar to illuminating gas, part of which is used to heat the coal. There may be a large excess however, which is used for industrial purposes after it has been purified.

Recently "coke oven" gas has been very successfully used in gas engines, and it will certainly be used to a much greater extent in the future.

Just as in the case of illuminating gas, tar and ammonia are by-products of coke ovens, and the tar is particularly valuable.

Air Gas.—In distilling coal to obtain gas, all of the fixed carbon is left behind as coke. As this can not be directly vaporized it is lost, so far as the gas making is concerned, unless some means of gasifying carbon indirectly can be found.

If the coal is heated and oxygen is supplied, carbon dioxide will of course be formed, but as this gas can not unite with more oxygen, it has no heating value. However, if carbon dioxide, CO_2, is passed over red hot carbon, it will absorb some of the carbon and form carbon monoxide, CO. The reaction is: $CO_2 + C = 2CO$. Carbon monoxide will combine with oxygen to form carbon dioxide; and it is therefore a combustible gas, although its heating value is very low.

These reactions, therefore, enable us to indirectly obtain solid carbon in a gaseous form. In practice the coal is burned with an insufficient supply of air. This air is sufficient to burn the first layers of coal, and carbon dioxide and steam are formed. The resulting heat of combustion makes the succeeding layers of coal hot and the volatile portion passes off as hydrogen, methane, etc., just as in the case of coal gas. These products form part of the final gas. A layer of red hot coke remains, and as the carbon dioxide passes over this hot carbon, carbon monoxide is formed. This absorbs heat, but the difference between the heat of combustion of carbon and carbon monoxide, which is considerable, exists as sensible heat in the carbon monoxide.

The steam is also decomposed by the hot carbon, forming more carbon monoxide and hydrogen. Here also the heat of combustion of the original hydrocarbon and of the carbon absorbed is greater than the heat of combustion of the carbon monoxide and hydrogen, and hence the difference exist as sensible heat.

That is to say, the heat of the "primary combustion" of the first layer of coal is not as great as the heat of combustion which can be obtained from the carbon monoxide and other products, which heat was absorbed when these products were formed. Hence the final gas is at a very high temperature. As it must be cooled before it can be used in a gas engine, a great loss would result.

Such gas is called "air gas," "power gas," "generator gas" or "Siemen's producer gas." It consists principally of carbon monoxide with nitrogen from the air used. There is also a small amount of hydrogen from the hydrocarbons of the lower zone, and hydrogen and hydrocarbons due to the distillation in the upper zone. When coke or anthracite is used, as is usually the case, there is but little of these gases. Air gas is used in furnaces and other places where it need not be cooled before burning. When produced as described, unmixed with other gases, it is too expensive for gas engine use.

Water Gas.—As has been stated, steam is also decomposed by hot carbon; the reaction being: $H_2O + C = CO + H_2$. This gives us another means of passing carbon into a gas, which is called "water gas."

In practice, an air blast is directed on a bed of anthracite coal or coke and enough coal is burned to render the whole bed incandescent. The air blast is then discontinued and a steam blast turned on. The steam is decomposed in passing through the hot bed of coal, forming hydrogen and carbon monoxide, both combustible gases. This mixture is well adapted for gas engine use, or heating purposes, but has no illuminating power. However, by mixing it with gases obtained by decomposing petroleum, "oil gas," which we will investigate later, a good illuminating gas can be obtained. The water gas is then said to be "carburetted." The illuminating gas of most large cities is a mixture of carburetted water gas and coal gas.

The decompositions of the water and the formation of carbon monoxide absorb heat, and hence the bed of coal, heated by the air blast, is soon cooled by the formation of the water gas. The steam is then shut off and the air turned on and enough coal burned to reheat the whole mass. The process is thus an intermittant one. The heated products of combustion are used to heat the air blast, so that no heat is lost, except a small amount due to the final heat of the water gas, which is at a somewhat high temperature.

In the "Lowe Water Gas Process," extensively used by the illuminating gas works in this country, the original air blast is used to produce air gas instead of carbon dioxide.

The heat of primary combustion heats the coal sufficiently, while the carbon monoxide is burned by a second air blast in chambers in which the oil for carbureting is decomposed. These chambers contain a quantity of loose fire brick called "checker work," and the air gas is burned in them during the time the air blast is on the main producers. Heat is stored in the checker work and afterward given up to the mixture of water gas and oil, which is led through the chambers while the steam blast is on the producers. The oil is thereby vaporized and decomposed.

Producer Gas.—When air gas is formed, a surplus amount of heat is formed which can not be utilized, while when water gas is formed heat is absorbed which must be supplied by extraneous methods. It is therefore possible to produce the two kinds of gas simultaneously in the same producer, in such proportions that the surplus heat of the air gas production forms the heat required for the water gas. The result is called "producer gas." Sometimes air gas is termed producer gas, but this is not strictly correct.

In practice a blast of air and steam is blown into a bed of coal. The air causes the lower layers to burn and carbon dioxide is produced. The heat of combustion heats the upper layers, and as the carbon dioxide and steam pass through decomposition takes place and carbon monoxide and hydrogen are formed. The air is so proportioned to the steam that the excess of the original heat of combustion over that absorbed when the carbon monoxide is formed, is just sufficient to supply the heat absorbed by the decomposition of the water. Some sensible heat is present in the final gases, owing to the high temperature at which the coal is maintained. This is sometimes used to heat the air blast.

Gas produced in this way will contain, theoretically, all the heat energy of the original coal. Of course practical losses occur, but high percentages are realized, from 70 to 80 % efficiency being common.

Anthracite Producer Gas.—Producer gas is most readily made from anthracite coal or coke. In this case the gas consists only of carbon monoxide and hydrogen, with the nitrogen of the original air and some carbon dioxide due to unavoidable excess of air and other irregularities. Very small amounts of various hydrocarbons may also be present. The gas is purified in a coke "scrubber," being led through a bed of coke over which water is trickling; it is then ready for immediate use.

The "Dowson" producer is the most common type of this class, and is in extensive use in England. It is made in sizes as small 80 H. P. Other types are also used in England and on the Continent, particularly in France. There very small producers are used, often as low as 40 H. P. Some of these small producers called "gasogenes" are really parts of the gas engine, as the gas is formed when the engine draws air and steam through the producer during the suction stroke.

However, in most cases a gas holder is provided and the producer is then independent of the engine.

Bituminous Producer Gas.—Owing to the absence of hydrocarbons, anthracite producer gas is comparatively easy to manufacture and may be used with but slight purifications. Bituminous coal contains hydrocarbons which may form tarry products in the producer, and in the various pipes, causing more or less trouble. The gas must also be subjected to more extensive purification in order to keep the tar out of the engine. Hence the production of bituminous producer gas is attended with some difficulty.

When bituminous coal is heated the volatile matter is at once driven off in a gaseous form, but these gases nearly all condense when cooled. Hence, if the volatile matter of the upper zone were allowed to pass off at once, a considerable amount of tar would be formed when the gas is cooled. Therefore a producer for bituminous coal usually has a chamber above the coal with no outlet. The volatile vapors collect here, and as they can not pass off they become heated and decomposed. In order to finally pass off, the gases must pass downward through some of the incandescent coal, whereby they are further decomposed. As the result of this decomposition hydrocarbons are formed, most of which are gases at atmospheric temperature, although some still remain which condense at tar.

In other respects the bituminous producer is similar to the anthracite. The purifying apparatus is more extensive in order that the tar may be thoroughly removed. If tar is carried over to the engine it is decomposed and a crust of carbon left on the valves, cylinder bore, etc., which causes leakage, and which is very difficult to remove.

The "Taylor" gas producer is used for bituminous as well as anthracite coal. It is the only producer used to any exextent in this country for gas engines.

The "Mond" producer has recently been introduced in England. It is arranged to recover the by-products, and these are often as valuable as the gas.

Producer Gas for Gas Engines.—Producer gas is probably the most economical fuel for gas engines used. Inasmuch as coal is the cheapest form of fuel at present, and producer gas is the cheapest gas from coal, it is certain to come into very general use as an engine fuel.

The cost of a producer gas plant is about the same as that of a boiler of equal power, and the efficiency is also about the same. As the gas engine itself is very much more efficient than the steam engine, the net result is much better. Therefore it is not surprising that producer gas plants and gas engines are being used instead of steam engines and boilers.

Of course the matter is somewhat new at present, and there are yet difficulties to be overcome.

A consumption of less than a pound of coal per brake horse power per hour is guaranteed by makers of producer gas plants of about 200 to 500 H. P. capacity; while a similar steam plant consumes about 2 lbs. of coal.

Other kinds of gas from coal are used in gas engines simply as a matter of convenience, the gas being made principally for illumination.

The enriching of illuminating gas, in order that it may give light in an ordinary gas burner, makes it more expensive and adds no value for gas engine purposes. When the "Welsbach" gas light is used, however, then only the heating value of the gas is important, and a good lighting gas is also a good engine gas. Some companies already make a form of producer gas solely for heating purpose, which gives light with Welsbach burners and power with gas engines. The more extensively such a gas is used the cheaper it will become. It seems quite probable that a gas of this kind will eventually be used exclusively, and then small power gas engines will be much cheaper to operate than at the present time. Hence it is to the interest of the gas engine to have the ordinary gas flame replaced by the Welsbach light.

It may be mentioned that carbon monoxide is poisonous to life and exerts much more than a suffocating action. Hence the maximum percentage of carbon monoxide is regulated by law in some places.

CHAPTER III.

Gases Not Obtained From Coal.

Natural Gas.—In many parts of the world a combustible called "Natural Gas" issues from the interior of the earth, either through natural crevices, abandoned oil wells or gas wells especially bored for this purpose.

This gas is well adapted for gas engine use and is extensively devoted to this purpose in the natural gas regions, particularly around Buffalo, Pittsburg, Indianapolis and the State of Ohio.

Owing to the criminal way in which natural gas is wasted by all who use it the supply is rapidly diminishing and the present fields will probably be quite exhausted in a few years.

Therefore it is not safe to erect engines which must depend on natural gas for a permanent supply, except in regions where the gas has recently been tapped and where it is to be used carefully and economically.

As the supply of gas in a region diminishes, the pressure at which it issues from the ground decreases, and finally the gas may actually have to be pumped out. In nearly all cases, if the gas is led in pipes for even a short distance, pumps must be used. The pressure of the gas at the engine is therefore variable and steadily decreases as time goes on. In order to secure a proper mixture of gas and air, provision must be made for this variation of gas pressure. With this exception, no especial provision need be made for using natural gas in a gas engine.

Natural gas consists principally of methane, with perhaps other paraffins, and small amounts of hydrogen, carbon monoxide and unsaturated hydrocarbons.

Blast Furnace Gas.—Pig iron is obtained from iron ore by treating it in a "blast furnace" in conjunction with coke or anthracite and some kind of flux. Part of the fuel is burned by means of an air blast, and under the influence of this heat the balance serves to unite with the oxygen of the iron ore, leaving more or less pure iron. The iron ore is either an oxide originally, or becomes one after being heated in the early stages of the process.

From the top of the furnace a gas issues, containing about 30% of carbon monoxide, a small amount of hydrogen and hydrocarbons from dissociation of water and volatile matter in the fuel, some carbon dioxide and a large amount of nitrogen. This gas is called "blast furnace gas," or in England "high furnace gas." It will usually burn, and is ordinarily used to heat the boilers which furnish steam for the blowing engines which supply the air blast.

Sometimes fuel is so cheap that the blast furnace gas is allowed to burn as waste, usually at the top of the furnace. In other cases the gas will not burn at atmospheric pressure. However, blast furnace gas can probably always be used in a gas engine. The heat due to compression, the possible lowering of the ignition temperature by compression, or the closeness of the particles when compressed may all all assist to produce the observed phenomenon, that blast furnace gas, even when too poor to burn in air, will drive a gas engine.

On account of the small content of the carbon monoxide, itself a very poor heating gas, blast furnace gas is always weak, and requires much greater cylinder capacity than other gases.

In England and on the Continent, particularly in Belgium, gas engines operated by the blast furnace gas are directly connected to the blowing engines which supply the air blast. This system replaces boilers heated by the blast furnace gas which furnished steam for steam-engines directly connected to the blowers. A marked economy has resulted, and the use of blast furnace gas engines is increasing rapidly. The system has been introduced into America at Buffalo and elsewhere.

Oil Gas.—As has already been stated, when hydrocarbons are heated without air, they decompose and form new hydrocarbons, finally forming some solid carbon. However, by proper regulation of the time and temperature the process of decomposition can be stopped at any desired point. In this way liquid hydrocarbons may be decomposed into liquid hydrocarbons of less density, and further heating decomposes these light liquid hydrocarbons into gaseous hydrocarbons. This process is termed "cracking."

When crude petroleum, refined petroleum, or any other oil composed of hydrocarbons, is properly heated in a closed retort, this cracking process results and hydrocarbons, which are gaseous at atmospheric pressure and temperature, are obtained. This result is "oil gas."

Oil gas is therefore composed of hydrocarbons which are gaseous under atmospheric conditions. A distinction must be made between oil gas and vaporized oil. When oil is merely vaporized the hydrocarbons are unchanged, and, if the vapor is cooled, a liquid will result. Oil gas may be made from the same liquid hydrocarbons, but they are decomposed and a new set formed which remain gaseous when cooled.

Of course, when oil vapor is used in a

gas engine the gasifier must be part of the engine. When oil gas is used the gas may be made in a separate apparatus.

Oil gas is used in England to drive gas engines, the oil being obtained by distilling certain varieties of coal.

Oil gas, as made by the "Pintch" process, is used all over the world for lighting railway coaches. This gas is probably too expensive for gas engine use.

In all oil gas producers some condensible hydrocarbons are produced in the form of tar, which must be removed before the gas can be used. There is also a residue of solid carbon in the retorts.

Gas from Refuse.—In making coal gas, solid hydrocarbons are rendered gaseous, and in making oil gas liquid hydrocarbons are gasified.

Other substances containing hydrocarbons will give gases under similar treatment, i. e., by heating in closed vessels. In this way gases available for gas engines use have been obtained from peat, saw dust, tan-bark, wood, etc., and it has been proposed to use animal fat, garbage, and other forms of refuse.

Acetylene Gas.—The solid calcium carbide, $Ca_2 C_4$, when brought together with water under ordinary atmospheric conditions, will combine and produce acetylene gas, C_2H_2, the reaction being $Ca_2 C_4 + 2H_2 O = 2 Ca O + 2C_2H_2$. Calcium carbide is now produced commercially by an electrolytic process, and acetylene gas is being widely used for lighting purposes. It is sometimes used on automobiles, but is too expensive for ordinary gas engine use, at present.

Carburetted Air.—When air is passed over gasoline, which has a high vapor pressure at atmospheric temperatures, the gasoline of course vaporizes until each cubic foot of air is saturated with enough gasoline to give the vapor pressure corresponding to the temperature.

However, if the air passes over quickly, and if the surface of the gasoline is limited, the air will lack more or less of complete saturation.

This is called "carburetted air" or

"gasoline gas," and consists of a nearly saturated mixture of gasoline vapor and air. As the vapor pressure of the gasoline is not quite up to that corresponding to the temperature, carburetted air can be cooled somewhat and still remain completely gaseous. Hence, for all practical purposes, carburetted air acts as a true gas.

Such a nearly saturated mixture of air and gasoline vapor will require to be mixed with a further large quantity of air before a perfect burning mixture is obtained.

Carburetted air is often made by an apparatus which forms part of the gas engine, and this aspect will be considered later. It is also made for lighting and heating purposes, and is then often used incidentally in gas engines.

There are two general methods of carburetting air. In one a tank of gasoline with passages of absorbent cloth is buried in the ground and the air passed through it. The heat of the earth supplies the latent heat of vaporization. In the other method the air is caused to bubble up through the gasoline, and the vaporization is facilitated by a gentle heat from an outside flame, or by steam heat.

The vapor pressure of gasoline vapor is such that the vapor of two gallons of gasoline, mixed with air to make 1000 cu. ft. of gas, will give a gas that will remain fixed under ordinary atmospheric conditions.

CHAPTER IV.

Gas Engine Gas in General.

Gas as a Fuel.—In all of the cases we have been considering, some form of gas has been produced by apparatus external to the engine; and the production does not directly concern us as engine designers.

However, in order to use the gas intelligently we have considered the general features of the production of all the more important methods of making gaseous fuel. Gas thus produced is fuel as far as the engine is concerned, although the original source of the gas is the actual fuel.

As we have mentioned several times, the substance actually burned in a gas engine is always gaseous. However, the fuel supplied to the engine itself may not be gaseous, and then its gasification is one of the problems to be considered by us in detail later.

Value of a Gas for Gas Engine Purposes.— The value of a gas for engine purposes depends upon the pressure which results after explosion. This depends directly upon the products in the clearance space after exhaust, the specific heat of the gas, the heat of combustion and the rate at which heat is lost to the jacket while inflammation is occurring. The rate at which heat is lost and the clearence products are probably the same for different gases in the same cylinder, and depends almost wholly upon the form of the cylinder and the total amount of heat generated. The "volumetric specific heat" or the heat which raises a cubic foot of the gas one degree, is practically the same for all of the mixtures we deal with, so that the final temperature and pressure of a cylinder full of gas does not depend upon the kind of gas.

Hence the only thing it is necessary to know is the total heat generated by the gas. In order to obtain the best results in most gas engines, the air and the fuel should be in about the proportions for perfect combustion. The air for the combustion of different gases varies greatly, and of course this air must enter the cylinder along with the gas. Therefore the criterion of the value of a gas for our purposes is the heat of combustion of a cubic foot of a perfect mixture of air and gas. We will later on discuss the method of obtaining the pressures, etc., from the heating value. At present we are only concerned with the fact that the power of a gas engine of a given size depends almost directly upon the heating value of the gas per cubic foot of perfect mixture. This, then, is the first thing to be computed or ascertained in designing a gas engine.

Table 1 gives the heat of combustion and air for combustion per cubic foot, for all of the usual elementary gases.

Table 2 gives a scheme for computing from these the heat of combustion per cubic foot of perfect mixture for any gas, from a volumetric analysis. Sometimes the density of the gas and the heat of combustion of a cubic foot of gas are also desired, and these are also calculated in Table 2.

However, the heat of combustion per cubic foot of gas gives little information to the designer, unless the air required can be found also.

Table 3 gives average volumetric analysis of various common gases, and the corresponding values of the heat of combustion per cubic foot of perfect mixture. This table shows the relative values of the various gases therefore.

Table 1.—Density, Heat of Combustion and Air of Combustion, for Gases.

Gas.	Formula.	Molecular Weight.	Density in grams per liter 0°C, 760 mm, 45°N. Lat. at sea level.	Density in pounds per cubic foot at 32°F. 14,-697 lbs. per sq. in.	Density in pounds per cubic foot at 60°F. and 14.7 lbs. per sq. in.	Specific Volume, cu. ft. per pound. 60°F, and 14.7 lbs per sq. in.	Higher value, heat of combustion. BTU per lb. 32°F. before & after combustion. Water condensed...............	Lower Value, heat of combustion, BTU per lb. 212°F. before and after combustion.	Lower Value heat of combustion. BTU per cu. ft. at 60°F and 14.7 lbs. per sq. in.	Cu. ft. of Air for perfect combustion of 1 cu. ft. of Gas.	Heating value per cu. ft. of perfect mixture.
Air..................	......	....	1.2932	.080732	.07638	13.092	....	....	....	...	....
Oxygen..............	O_2	31.76	1.4295	.0892405	.08442	11.846	....	....	....	....	....
Nitrogen...........	N_2	27.86	1.2571	.078478	.07424	13.470	....	....	....	....	....
Carbon Dioxide......	CO_2	43.66	1.9780	.12351	.11683	8.560	....	....	....	....	....
Carbon Monoxide...	CO	27.78	1.2520	.07818	.07396	13.520	4380	4380	324	2.386	95.67
Hydrogen	H_2	2.00	0.08995	.0056154	.005311	188.29	62100	52230	277	2.389	81.72
Methane (Marsh Gas)	CH_4	15.90	0.7212	.04504	.04261	23.470	24000	21520	917	9 637	86.23
Ethane	C_2H_6	29.80	1.3900	.08681	.08212	12.177	22340	20350	1671	17.35	91.06
Ethylene	C_2H_4	27.80	1.2743	.07958	.07528	13.284	21900	20480	1542	14.61	93.78
Propylene...........	C_3H_6	41.70	1.9375	.12100	.11445	8.737	21420	20000	2289	22.21	98.62
Butylene	C_4H_8	55.60	2.5800	.16110	.15240	6.562	20900	19480	2968	29.59	97.03
Benzine Vapor	C_6H_6	77.40	3.5900	.22420	.21210	4.715	18090	17330	3675	36.96	96.81
Acetylene....	C_2H_2	25.80	1.1900	.07431	.070290	14.227	21860	21100	1483	12.25	111.92

Table 2. Sample Gas Calculation from Analysis. Illuminating Gas.

Components.	Formula	Volumetric Analysis. Cu. ft. per cu. ft. Gas.	Density, lbs. per cu. ft.	Weight of each component per cu. ft. of gas.	Lower value heat of combust. per cu. ft.	Heat of combst. of each component per cu. ft. Gas.	Cubic ft. air for combst. per cu. ft. of component.	Cubic ft. air for combst. of each comp. per cu. ft. Gas.
		V	D	D × V	H	H × V	A	A × V
Light Hydrocarbons taken as Benzine	C_6H_6	.006	.2121	.00127	3675	22.05	36.96	.222
Heavy Hydrocarbons taken as Propylene	C_3H_6	.038	.11445	.00435	2289	86.99	22.21	.844
Carbon Monoxide	CO	.076	.07396	.00562	324	24.63	2.386	.181
Oxygen	O_2	.008	.08442	.00068	....	....	....	....
Methane	CH_4	.362	.04261	.01543	917	331.90	9.637	3.489
Hydrogen	H_3	.398	.005311	.00211	277	110.24	2.389	.951
Nitrogen	N_2	.112	.07424	.00832	....	....	....	....
....	....	1.000	....	.03778	....	575.81	....	5.687
Deduct for air not needed on account of O in gas 4,782 x.008								.038
								5.649

Table 2.—*Continued.*

RESULTS.—Density of Gas .03778 lbs. per cu. ft. at 60° F. and 14.7 lbs. per sq. in.

Lower value heat of combustion—575.8 B.T.U. per cu. ft. of gas at 60° and 14.7 lbs. per sq. in.

Lower value heat of combustion $= 575.8 \div (1 + 5.649) = 86.6$ B. T. U. per cu. ft. of perfect mixture.

Ratio of air to gas, perfect mixture $=$ 5.649.

(NOTE—Values of D.H. and A. are to be taken from Table 1.)

Table 3.—Heat of Combustion of Gases used in Gas Engines. Best Obtainable Average Values.

GAS.	Average Volumetric Analysis. CO_2	N_2	CO	H_2	CH_4	Unsat. Hydrocarbons as C_3H_6.	Lower value heat of combst. cu.ft. of gas at 60°—14.7 lbs. per sq. in.	Cubic. foot of air per cubic foot of Gas. Perfect mixture.	Lower val. heat of combst. per cu.ft. of perfect mixture at 60°—14.7 sq. in.
Coal Gas (Illuminating)	.02	.03	.05	.45	.40	.05	622.1	6.159	86.9
Coal Gas Weakest Explosive Mixture	....	....	....	....	....	......	622.1	13.000	44.4
Coke Oven Gas..	.02	.18	.03	.57	.19	.01	364.7	3.487	81.3
Air, or Siemen's Producer Gas, Theoretical........	....	.65	.35	....	....	.. ..	113.4	0.835	61.8
The Same, actual	.04	.62	.23	.08	....	.03	165 4	1.406	68 7
Water Gas (theoretical)	....	....	.50	.50	....	......	300.5	2.388	88.7
Water gas (actual)	.03	.04	.44	.49	....	......	278.2	2.220	86.4
Water Gas (Carburetted)..............	.04	.04	.25	.35	.18	.14	663.3	6.277	91.2
Producer Gas (theoretical)	....	.45	.39	.16	....	......	170.7	1.312	73.8
Producer Gas Anthracite....	.07	.47	.27	.18	....	.01	160.3	1.296	69.8
Producer Gas Bituminous..........	.04	.50	.22	.20	....	.04	218.3	1.890	75.5
Natural Gas.....	....	.08	....	.02	.90	.....	830.8	8.721	85.4
Blast furnace Gas	.10	.58	.30	.02	....	......	102.7	0 764	58.2
Oil Gas	....	.07	....	.31	.46	.16	874.1	8.727	89.9
Acetylene gas (pure	....	....	....	....	....	......	1483.0	12.250	111.9
Carburetted Air, or gasoline gas, 2 gals. gasoline per 1000 cu. ft	....	....	....	....	....	......	214.2	1.203	97.2
Pure Gasoline Vapor	....	....	....	....	....	......	4000	40.0	97.2
Pure Kerosene Vapor at 150°	....	....	....	....	....	......	2526.0	31.110	78.7
Taylor Anthracite av.	.084	.527	.183	.174	026		131.3	1.075	63.3
Taylor Anth. min.	.091	.569	.160	.152	.023		115	.913	59.2

Weak Gases.—If the heat of combustion per cubic foot of perfect mixture is too low the gas will not explode. The exact values when this occurs are not very well known and are dependent on a variety of conditions. A few approximate values for weak mixtures are given in Table 3. These will serve as a guide in deciding whether or not experiments should be made to determine the explosiveness of a gas. This is, of course, the only true criterion.

Impurities in Gases.—Another point in connection with a gas which interests the engine designer is the purity. Of course dilutants, such as nitrogen, carbon dioxide, etc., are inert and do no harm.

In rare cases it might be possible that a gas could contain certain impurities which would injure the cylinder walls or decompose the cylinder oil. Nothing of this kind has been observed so far as known.

A gas frequently contains tar and grit however. The tar leaves a deposit on the interior surfaces of the engine, and the grit causes the cylinder to be cut. Both the tar and the grit can be removed by sufficient purification. However, if the designer is at all suspicious that this may not be done properly, the engines should be so designed that it may be easily cleaned in the case of tar, or that a new cylinder liner may be put in in the case of grit.

CHAPTER V.

Liquid Fuels.

Use of Liquid Fuels.—As has been stated, the fuel to be burned in the gas engine is often supplied in a liquid form, and then a gas making apparatus forms part of the gas engine. We will here briefly consider the origin and nature of liquid fuels, and in another place the means of gasifying them.

Alcohol.—Ethyl Alcohol or Grain Alcohol, C_2H_6O, made from fermentation of grain, potatoes, etc., and methyl alcohol or wood alcohol, CH_4O, made from the distillation of wood, are both used for small gas engines in some parts of the world where the alcohol can be cheaply made. They are used in very much the same manner as is gasoline, which latter fuel we will consider later.

Petroleum.—In many parts of the world "oil" wells have been bored which yield a heavy oil called "petroleum." The most important oil regions are at present in the vicinity of the Caspian Sea in Russia, in Pennsylvania, Ohio, West Virginia, California and Texas.

"Crude Petroleum," as it rises from the ground is a mechanical mixture of many different hydrocarbons, mostly paraffins, with some sulphur and other impurities. Crude oil is sometimes used directly as an engine fuel, being vaporized by the aid of heat.

The hydrocarbons of crude oil have widely varying densities, boiling points, etc. By the process called refining, products are obtained which are purer and each of which contains a fewer number of hydrocarbons than the original oil.

Refining is accomplished mainly by fractional distillation, and each product therefore contains a number of hydrocarbons with contiguous boiling points. Just what these hydrocarbons are is not known however.

Light Petroleum Products.—The first results of the distillation are called Rhigolene, Cymogene, etc., and are easily vaporized. They are rather dangerous, as an explosive mixture is quickly made when they are exposed to the air. They have not been used to any great extent for gas engines.

Gasoline.— The members of the next series of products are called "gasolines." They are graded according to their specific gravity when measured on the scale of the Beaume Hydrometer. The lightest product is 86° gasoline which vaporizes so readily that it is rather dangerous. It is not often used for gas engine purposes. The next member is 74° gasoline, formerly called benzine. This was the original gas engine liquid fuel. 69° gasoline is now the gasoline of commerce, although it was formerly called "naphtha." It is now easily vaporized so that the lighter and more dangerous gasolines are seldom used.

The vapor pressure of gasoline at atmospheric temperature is so high that a mixture of air and vapor much too rich to explode can be made by bringing together or mixing air and liquid gasoline in some way or other.

Hence, when gasoline is exposed to the

air, the surrounding atmosphere may be filled with an explosive mixture. In this way a leaky tank of gasoline may be ignited by a light, perhaps 20 feet away. Therefore due precautions must be taken in handling gasoline, and in storing it for engine use. Most insurance companies specify that gasoline must be stored in an underground tank and pumped out just as needed for use in the engine.

In England the restrictions as to the use of gasoline are so great that it is probably never used for gas engines. English writers speak of gasoline as "petroleum spirits," and seem to think that it is more dangerous than nitro-glycerine, and absolutely impossible to use. This is absurd, as there are thousands of stationary gasoline engines in use in this country, with outside underground tanks, none of which have ever exploded or given trouble with fire.

Kerosene.—The next heavier distillates are called "kerosene," or "coal oil." These have low vapor pressure and do not form an inflammable mixture when exposed to the air at ordinary temperatures, and hence do not require any especial precautions.

The criterion, whether an oil is safe or not, is the "flash test." This test gives the "flashing point" or the temperature at which the vapor pressure becomes great enough to form an inflammable mixture or vapor with the surrounding air. The legal safe flashing point in England and in some parts of America is 100° if the kerosene is in an open vessel, corresponding to about 73° if a closed vessel is used.

Kerosene will not therefore give a gas which we can use, unless its temperature be raised. A more extensive apparatus is therefore required to vaporize kerosene than in the case of gasoline.

Kerosene is much used as an engine fuel in England, as the use of gasoline is practically prohibited. Kerosene is also extensively used for heating and illuminating, and is the most important of the petroleum products.

In order to increase the yield of kerosene the distillation process is so conducted that some of the paraffine hydrocarbons are cracked. This gives light olefins from paraffines too dense to enter into kerosene without unduly increasing the difficulty of vaporizing it. Hence kerosene contains olefins as well as paraffins.

The latent heat of vaporization of kerosene is about 1100 BTU, and the specific heat is about .47.

Distillate.—Sometimes a petroleum product about resembling kerosene but not purified as much, is produced instead of kerosene and gasoline. This is called "distillate" and is used in an engine in the same way as kerosene.

CHAPTER VI.

Discussion and Calculation of Cylinder Action. Exhaust and Admission.

General Cylinder Problem.—As our cylinder walls are not impermeable to heat they absorb some of the heat liberated by combustion, and their temperature is raised to a considerable extent. In order to keep the wall temperature below the ignition point of the lubricating oil, a water jacket is used, and some of the heat of combustion passes through the walls to the water and is lost. Sometimes the velocity of flame propagation is low enough to cause the combustion to last while the piston is moving forward; this cuts off the peak of the diagram. As the gases expand more heat is lost to the cylinder walls. Sometimes the combustion is prolonged through expansion. Early release cuts off the corner of the card, and there is back pressure due to friction in the exhaust valve and pipe. When the new charge enters it is heated up by the cylinder walls and the hot burnt gases remaining in the clearance. Owing to friction of the ports, pipes, etc., the pressure at the end of admission is less than atmospheric. This increase of temperature and decrease of pressure causes a considerable decrease of density. Hence the charge drawn in during admission if reduced to atmospheric conditions would not nearly fill the piston displacement.

Some of the above conditions cause a definite loss, while others merely cause a departure from the theoretical conditions.

One problem of the designer is to discover methods whereby all of the losses may be reduced to a minimum. Another consists of the calculation in advance of the actions which will take place in an engine, in order that it may yield a given amount of power and have proper strength of parts. We will be compelled to resort almost wholly to empirical data in solving these problems.

We will proceed to discuss in detail all of the actions occurring in an Otto cylinder, beginning with the interchange of the products of combustion and the new charge.

Release. — Theoretically, the exhaust valve should begin to open or "release" exactly at the end of the stroke. However, as the valve must open gradually, if it began to open at the end of the stroke it would not reach full opening till the piston had advanced some distance on the exhaust stroke. Actually it is found best to have release occur somewhat before the end of the expansion stroke, so that at the beginning of the exhaust stroke the valve will be open by an amount called the "exhaust lead." The pressure in the cylinder at the end of expansion is considerable as we have already seen. It will perhaps average 25 lbs. gage in ordinary cases. In order that enough exhaust may pass out to reduce the pressure within the cylinder to atmospheric pressure in a reasonable time, the exhaust lead must be considerable.

The object to be attained is to secure the greatest possible area of the tail of the card. (Fig. 1 shows the best conditions that can be realized.) The only accurate way to do this is to take cards and change

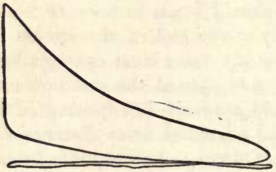


Fig. 1.

the exhaust setting until a good result is obtained. In most cases this is not done, but the valve is set by guess. Under such conditions release usually occurs too late. Indeed, many of the poorer engine builders, who have never seen a card from their engines, open the exhaust at the end of the stroke.

Inspection of actual cases shows that the exhaust valve should begin to open when the piston is from 87.5% to 95% from the beginning of the stroke. For ordinary lengths of connecting rod, the angle between the crank and the horizontal will then be from 45° to 28°. This is the extreme range, and most cases come between these limits. If the exhaust opens later than 95% of the stroke the area is almost certain to be cut down.

In designing a valve gear, the best method of procedure is to lay out the motion to release at about 92%, the corresponding crank angle being 35°. The cam, eccentric or mechanism moving the valve should not be set positively until the indicator cards are taken. The setting can then be corrected one way or the other until a good set of cards are obtained; and then the key ways, etc., can be finally cut. When this can not be done and no better value is at hand, the setting of 92% and 35° may be taken as being correct for an average case. The rate at which the exhaust valve moves should be as great as possible. Sometimes an exhaust port in the side of the cylinder is uncovered by the piston at the end of the stroke. The whole exhaust passes out in this manner in "two cycle" engines, and such a port is also used to assist the exhaust valve in some four cycle engines.

For two cycle engines this port should begin to open at about 87.5% or $^7/_8$ stroke; while in four cycle engines, where the port does not take the whole exhaust, the opening should begin at about 92% of the stroke.

Exhaust.—As the piston moves back on the exhaust stroke the burnt products pass out through the exhaust pipe. There will be friction in the various ports and pipes through which the exhaust passes in reaching the atmosphere. Hence, in order to force the exhaust out against the friction, a pressure greater than atmospheric must exist within the cylinder. This pressure is maintained by the motion of the piston. On the outside of the piston atmospheric pressure exists, and hence the excess pressure in the cylinder opposes the motion and causes a loss. This loss is shown by the fact that the exhaust line on the indicator card is above the atmospheric line.

The pressure difference required to overcome the friction occurring when a gas passes through pipes, is approximately proportional to the square of the velocity. The larger the exhaust passages the less will be the velocity, since the volume rate is constant. Since the pressure difference varies with the square of the velocity; as the velocity increases the pressure difference increases rapidly at first, but more slowly afterward. Hence, if the exhaust pipe is too small a slight increase will cause a considerable decrease in the pressure difference, but further increase will have but slight effect. For the same reasons if one size of exhaust pipe is about right a small decrease will cause a considerable back pressure, but an increase will have little effect.

Similar considerations apply to the inlet pipes and ports.

Sizes of Ports and Pipes.—The sizes of pipes and ports for both inlet and exhaust are decided by assigning an empirically determined value for the average speed of the gases. This value ranges from 4000 to 6000 feet per minute, according to circumstances. Higher speeds than these are often used, but the friction loss is then probably increased to an undue extent. Slightly lower values of the speed give somewhat better results with increased cost.

The diameter of a pipe is computed from the allowed velocity, as follows: The volume passing through the pipe must be equal to the cylinder displacement, hence we have the following:

$\frac{\pi}{4} d^2. (l.2n) = (12\,S)\frac{\pi}{4}. p^2$, where d and l are the cylinder dimensions in inches, n the *r. p. m.*, p the pipe diameter and S the allowed speed in feet per minute.

$$\text{Then} \qquad p = d.\sqrt{\frac{l\,.\,n}{6\,S}}.$$

If s be the piston speed in feet per minute.

$$p = d.\sqrt{\frac{s}{S}}$$

A common value for the piston speed for small and medium engines is 600. Taking 6000 as the exhaust and inlet speeds we have, inlet or exhaust pipe diameter=

$0.32 \times$ cyl. diam. The nearest standard pipe sizes must, of course, be used. All of the passages between the outer air and the cylinder should be kept of the same size.

The valves used are usually poppet valves, and then the bore below the valve seat should be of the calculated size. There is a slight resistance due to the valve stem, but this is unimportant.

The lift of a poppet valve should be such that the circular ring, whose height is the lift and whose diameter is the valve diameter, has a surface equal to the valve area below the seat. If L is the lift and p the diameter then

$$\pi . p . \mathrm{L} = \frac{\pi}{4} p^2 \text{ or } \mathrm{L} = p/4.$$

That is, the theoretical lift of a valve is $^1/_4$ its diameter.

In order that the opening be sufficient in the earlier part of the valve motion the lift is often made greater. However, this is usually unnecessary if the valve opens with reasonable rapidity.

Exhaust Closure. — When the piston reaches the end of the stroke and starts to return, the exhaust valve closes and the inlet valve opens. In order that the exhaust valve should have an appreciable opening right up to the end of the stroke, it should not close completely until the piston has passed the center and moved forward slightly. There will be no danger that the exhaust be sucked back into the cylinder, even if the valve is not closed until 5% of the forward stroke. If the air valve is opened in time the reverse will occur and air will pass out through the exhaust instead, as will be seen later. However, some designers fear sucking back of the exhaust and close the exhaust valve precisely on the dead center.

After we have forced out all the exhaust possible there still remains some in the clearance space, which forms a considerable fraction of the displaced volume in an Otto engine. This will remain and mix with the gas and air taken in during the next stroke. The exhaust is always at a high temperature, and it therefore heats up the new charge. The hot cylinder walls cause further heating. Now the volume which the new charge will occupy is the cylinder displacement in ordinary cases. Heating up the entering charge diminishes its density and therefore its amount, and consequently diminishes the amount of heat liberated by the explosion. Hence, the power obtained from a given size of cylinder is decreased, owing to the heating of the entering charge.

Effects of Scavenging.—If by any means we can get rid of some of the clearance exhaust, we would secure a valuable advantage. This is termed "scavenging" and may be accomplished in several ways which we will discuss presently.

In the first place, scavenging enables a larger actual volume of new charge to be taken in, in order to replace that portion of the clearance exhaust which was gotten rid of. Secondly, the smaller quantity of exhaust gases and larger volume of new charge will reduce the temperature to which the new charge is brought by being mixed with the exhaust and being heated by the cylinder walls, hence the density of the new charge as it enters the cylinder is increased, which further increases its amount. Therefore scavenging greatly increases the power obtained from a given size of cylinder. Owing to the decreases in the initial temperature of the cylinder contents the final temperatures attained are not so great, and hence the loss to the jacket water is decreased. Hence scavenging will slightly increase the efficiency of the engine if the compression is unchanged. However, scavenging enables a higher compression pressure to be carried without danger of pre-ignition, owing to the reduction of the initial temperature. This causes considerable increase in efficiency.

Automatic Scavenging.— When the exhaust is first opened there is a sudden rush through the exhaust valve which sets the whole column in the exhaust pipe in motion. This motion is kept up during the return of the piston, and during the latter part of the stroke the inertia of the column in the exhaust pipe causes the gases to leave the cylinder faster than the piston displaces them, which causes a reduction of the pressure in the cylinder. The radiation of heat from the exhaust pipe causes a cooling and contraction of the column within, and this causes a further rush of gases from the cylinder and consequent reduction of cylinder pressure. If the exhaust pipe be straight and sufficiently long (65 ft. in some cases) and all of the passages shaped so as to reduce friction, the pressure within the cylinder will be somewhat less than atmospheric pressure during the latter portion of the exhaust stroke. The inlet valve is arranged to open at this period and hence air will begin to enter the cylinder even before the piston reaches the end of the exhaust stroke. When the piston starts on the return stroke the exhaust valve is still held open, as exhaust will continue to pass out until the piston has proceeded some distance, owing to the inertia and cooling action. The exhaust valve then closes and admission proceeds in the usual way. There is usually a separate gas valve operated by a hit or miss governor where this system is used. The gas valve opens as the exhaust closes.

The best results are said to be obtained when the exhaust valve opens with the crank at 45° above the center, and closes with the crank also above the center, 45° being 270° from the point of opening. The inlet valve is opened when the crank is 45° below the center. Hence for 90° during the end of the exhaust stroke and beginning of the admission stroke, the inlet and exhaust are open together and air is said to come in and exhaust go out during the whole of this time. Air only can enter, as the gas valve does not open until the exhaust closes.

This system of scavenging was originated by Crossley and Atkinson. It operates very successfully when the exhaust pipe is properly designed.

In some cases the power obtained from a given sized cylinder has been increased 30%, partly owing to the increase of charge taken in, and partly owing to increased compression pressure permitted with the cooler gases.

The exact circumstances which cause or destroy these effects are not well understood. American builders do not seem to seek automatic scavenging to any great extent.

Scavenging is sometimes accomplished by forcing air through the clearance space at the end of the exhaust stroke by means of an extra pump, by the use of a six stroke cycle or by some special piston mechanism.

Admission Pressure.—The air and fuel are admitted to the engine in various ways, according to the system of governing. However, there is usually an inlet valve opening directly into the cylinder by which the previously mixed charge enters. There may be various other valves in the pipes leading to the inlet valve.

When the piston advances on the admission stroke the air, and the fuel enter through various valves and pipes, and owing to friction losses, are at less than atmospheric pressure when the cylinder is reached. The admission line of an indicator card is therefore slightly below the atmospheric line. This reduction of pressure causes a reduction of density, and hence a reduction in the quantity of the charge per stroke. This effect is shown on the card as in Fig. 2, which shows admission and beginning of compression.

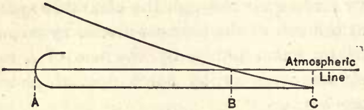


Fig. 2.

Owing to the reduction of the suction pressure the charge, when brought to atmospheric pressure by the advance of the piston, occupies a volume proportional to A B, whereas if there had been no pressure drop, the volume would be proportional to A C. This reduction in the amount of the charge cuts down the heat developed per explosion and also cuts down the compression pressure. Both of these causes reduce the power developed with a given size of cylinder. Reduction of suction pressure therefore gives one method by which an engine may be governed. A throttling valve operated by the governor cuts down the amount of air and gas simultaneously by reducing the admission pressure, thus keeping the proper proportions. This valve should be the only place where throttling takes place however. All of the other pipes, ports, etc., should be of such size that when the governor holds the throttling valve wide open for full load, the admission line will be kept but little below the atmospheric line.

In hit or miss engines the admission line must always be close to the atmospheric line.

Sizes of Inlet Ports or Pipes.—In order to secure this high admission line and still have control over the relative amount of air and gas necessary for proper explosions, the following conditions should be met.

All pipes and valves through which the mixed charge must pass should have an area such that the mean velocity of the gases, calculated from the piston displacement, will not exceed 6000 feet per minute. All pipes and ports and valves through which the air passes before mixing with the fuel should have a proportionate area calculated from the ratio of air in a perfect mixture. The area of the gas or oil pipe is not so easily calculated, as the fuel is always supplied under pressure.

The fuel pipe should be large enough to admit fuel enough to use up all of the air which is admitted by the air pipe.

In an actual engine the proportions are adjusted by trial so as to secure a good explosion, by means of regulating valves in the air and the fuel pipes. Adjustment is made by throttling the fuel supply, if possible, leaving the air pipe free. If, however, the fuel pipe is too small it must be left wide open and the air supply cut down to suit, by throttling. This evidently decreases the quantity of mixture admitted, lowers the admission line, and cuts down the power of the engine. On the other hand, if the final regulation can be accomplished by simply throttling the fuel supply and leaving the air pipe wide open, we are sure that the fuel pipe is too large, as it should be for safety.

The fuel supply is best regulated by opening the fuel regulating valve as wide as possible consistent with good explosions, and then gradually closing it. The power developed will increase slightly as this is done, as the original setting caused an excess of fuel. Presently the power will begin to decrease as the fuel valve is further closed, and the point at which this decrease begins gives nearly a perfect mixture. For best results the fuel valve should be set slightly below this point, so as to give a slight excess of air. This is the setting for maximum power. Maximum economy, minimum fuel consumption per horse power, is usually secured with a somewhat greater excess of air, and of course less total power. The engine will continue to explode with a considerably less fuel opening and greater excess of air than this, but a point is soon reached where the mixture becomes too dilute to explode. Governing is sometimes attempted by thus diluting the mixture. Only as mall range is possible however, and the air must be reduced with the fuel for good results.

Owing to the diversity of pressure at which gas engine fuel is supplied, it is not possible to formulate a general rule for sizes of fuel pipes. When the fuel is at a low pressure, as in the case of illuminating gas, the pipe may be calculated from the piston displacement and ratios of gas in the mixture, allowing a velocity of 10,000 feet per minute. When the supply pressure is higher a higher velocity may be allowed, depending on circumstances.

Often a gas pipe leading to an engine from a distance has its capacity increased by the use of a "gas bag." This in a rubber bag or vessel with one or more rubber diaphrams as walls placed on the gas pipe close to the engines. The gas pressure distends the rubber, and when the engine sucks a charge the contraction of the bag helps out the supply from the pipe line. As the suction is intermittent the gas bag is filled between times. A gas bag can only help out a small pipe line, and cannot overcome the effect of small passages for the gas between the gas bag and the interior of the cylinder.

If oil or other liquid fuel is used, the velocity should not exceed 250 feet per minute. The velocity may be calculated with sufficient accuracy by assuming a fuel consumption of a pint per horse power hour. It must be noted that the fuel only flows into the cylinder during one-fourth the time.

Admission Valve Setting.—There is usually a valve which admits the mixed charge directly into the cylinder, and which is called "the inlet valve." This valve is to be open when the piston is moving forward, and when there is slightly less than atmospheric pressure in the cylinder. At all other times there is more than atmospheric pressure in the cylinder. Hence a simple check valve opening inwards could be used. This would open automatically when the piston was making the admission stroke and would be kept closed by the internal pressure at all other times.

However, to insure certainty of action a light spring must be used to close the valve, and then the pressure difference between the cylinder and atmosphere must be great enough to overcome the force of the spring. The valve would also be late in opening for a similar reason. Hence such an automatically operated inlet valve causes a low admission line, and therefore cuts down the power of the engine for reasons that we have already discussed. Accordingly all good engines have a mechanically operated inlet valve. In order that it should have an appreciable opening when the piston starts on the admission stroke, the inlet valve should begin to operate or open at from 95% to 100% of the exhaust stroke. It should close at the end of the admission stroke or very early in the compression stroke, say about 2%.

As we have already seen when automatic scavenging is designed, the inlet valve opens at 82% of the exhaust stroke.

In the most usual form of hit or miss engines, a valve called the "fuel valve" opens into the air pipe just before the main inlet valve. This valve is mechanically operated when tne governor permits. It should be opened after the exhaust valve has closed in order to remove the remote possibility that gas will escape into the exhaust pipe.

So long as the fuel valve is not open the inlet valve and exhaust valve may be opened simultaneously for a short time at the end of the exhaust and beginning of admission. Then, even in the improbable cases that some of the air will pass into the exhaust pipe or exhaust passes into the air pipe, the fuel will be safe. The fuel valve should close at about the end of the admission stroke. In some cases, where the governing is obtained by reducing the fuel supply only, the time at which the fuel valve opens and closes varies. The total time that the fuel valve is open is then automatically regulated by the governor.

Admission Temperature.—When the admission stroke is ended and the piston starts to compress, there is within the cylinder a volume of fresh charge about equal to the piston displacement, and a volume of burnt gases about equal to the clearance volume. The fresh charge, in entering has become more or less heated by mixing with the burnt gases and by absorbing heat from the cylinder walls. These actions cause the charge to have a rather high temperature at the beginning of compression. Experiments have shown that this temperature ranges from 200° to 300° Fahrenheit. This temperature is often stated to be near the final temperature of the jacket water, but such an assumption is greatly in error.

We have already considered the general effect of a high admission temperature in decreasing the amount of charge contained in the cylinder volume, and so decreasing the power obtained from a given cylinder. We have also considered the effect of scavenging in reducing the admission temperature. Now let us consider the effect of the cylinder walls on the admission temperature. By the use of jacket water the temperature of the walls, at the time the piston passes over them, is somewhat below the burning point of the cylinder oil.

Hence, when the piston uncovers the walls after exhaust, they are still very hot and transfer some of the heat to the new charge which was initially at atmospheric temperature.

The cooler the cylinder walls are the less heat will be given up to the new charge. For this reason an increase in the quantity of the jacket water causes an immediate increase in the power of an engine. This effect is very marked and shows conclusively the effect of the walls in increasing the temperature and so decreasing the quantity of charge per stroke. However, when the walls are thus kept cooler the loss of heat during the explosion and expansion is increased, and hence the economy is decreased. That is, when the power is increased by cooling the walls the total fuel consumption is increased in a greater ratio, and hence the fuel consumed per horse power hour is increased.

We, of course, assume that the compression pressure is not changed. However, the cooling of the cylinder walls allows a higher compression pressure to be used without pre-ignition, and if this is done the economy is increased.

The walls of the clearance space, the exhaust and inlet valve ports and the back of the piston are not lubricated and do not have to be cooled for this purpose. However, if they were not partially jacketed they would be so hot as to cause pre-ignition with very low compression pressures, and also immediately reduce the quantity of charge per stroke and cut down the power correspondingly. Therefore modern practice is to thoroughly jacket the clearance space, and particularly the exhaust and inlet valve ports and their vicinity. In large engines the back of the piston is jacketed also. This is done primarily to enable high compression pressures to be carried, but also to increase the power of a given size of engines, by increasing the amount of charge.

The absorbtion of heat by gas depends principally upon the rate of its circulation over a hot surface. Very little heat is absorbed by radiation or conduction between parts of the gas. Hence, if the passages through which the main current of the entering charge flows are kept cool by jacketing, the temperature of the charge will be kept down, even though other parts of the walls where circulation is not so rapid, are at a higher temperature. For this reason it is advisable to keep the entering charge away from the exhaust valve. Some builders do not jacket the vicinity of the exhaust valve at all, but keep this valve cool by having the entering charge pass over the top. This keeps the valve cool nicely, but heats up the charge enough to cause a perceptible reduction of power.

Effect of Speed on Admission Pressure.—If the valves, ports, etc. are of sufficient size, the admission line may be kept close to the atmospheric line, no matter what the speed of the engine. However, if the ports are proportioned for a certain speed, then an increase of speed gives an excessive velocity of gases through the ports, lowers the admission line and cuts down the quantity of charge per stroke. When the speed of an engine is successively increased, a point is soon reached where the amount of charge per stroke drops off faster than the power increases. Hence the total power developed by an engine will decrease when the speed is increased, for very high speeds.

CHAPTER VII.

COMPRESSION.

Compression Index.—When a perfect gas is compressed the relation between pressures and volumes is:

$$\frac{p_1}{p_0} = \left(\frac{v_0}{v_1}\right)^n = \left(\frac{1 + c}{c}\right)^n$$

Here p_0 is the pressure at the beginning of compression, p_1 is the final compression pressure, v_1 is the clearance volume and v_0 is the piston displacement plus clearance, c is the percentage of clearance; n is the index of the compression curve and becomes equal to k for adiabatic compression with a perfect gas, being 1.405 for air. For the products in a gas engine cylinder k is somewhat less than 1.405 at ordinary temperatures. The index for adiabatic compression of an imperfect gas is still less, and gradually decreases with the temperature, owing to the increase of specific heat.

We should expect nearly adiabatic compression in an average gas engine for the following reasons: During admission the entering charge is heated by the cylinder walls, and this action probably continues during the early part of compression. The charge is heated while being compressed however, and presently it is hotter than the cylinder walls, and gives up some heat to them during the latter part of compression. Experiments have shown that these amounts of heat nearly equal each other, so that the net effect is nearly the same as if there had been no exchange of heat between walls and charge. Hence, we should have nearly the same final result as if there had been adiabatic compression, whence the index for compression should be somewhat less than 1.405. Calculation from actual indicator cards show that the index varies from 1.25 to 1.35, a mean value being 1.3.

Compression Pressure.—We have already seen that the pressure in the cylinder, when compression begins, is less than atmospheric pressure, owing to the friction in the admission pipes. An average value is about 13 lbs. per sq. in. or 1.7 lbs. less than atmospheric pressure. With large inlet valves the pressure may rise to 14 lbs., and in poor cases it may be 12 lbs. Hence the absolute pressure at the end of compression has the average value

$$p_1 = 13 \left(\frac{1 + c}{c}\right)^{1.3}$$

where c is the clearance volume expressed as a percentage of the piston displacement.

From data collected from a large number of tests of gas engines, probable values of the clearance to produce a given compression pressure have been selected, and are given in table 4. These values agree fairly well with the above formula, but not exactly. The tabulated values are slightly more trustworthy, as they are representative of actual tests.

Table 4 also gives average observed values of mean effective pressure, which are discussed later, in Chapter X.

TABLE 4.

Empirical Values of Clearance and Mean Effective Pressure.

Compression Pressure. Lbs. per sq. in. Gage.	Probable Clearance as per cent. of Displaced Volume.	Mean Effective Pressure.						
		5 B. H. P. and under.	10 B. H. P.	25 B. H. P.	50 B. H. P.	100 B. H. P.	200 B. H. P.	500 B. H. P.
50	40	60	65	70	75	—	—	—
60	35	65	70	75	80	—	—	—
70	30	70	75	80	85	85	90	95
80	28	70	75	85	90	90	95	100
90	26	—	—	90	95	95	100	105
100	24	—	—	95	95	100	100	110
110	22	—	—	95	95	100	100	110
120	20	—	—	—	—	100	100	110

Of course circumstances vary so much that no table or formula can always predict exact results. Hence, when the first of a new type of gas engines is to be built, the clearance is made adjustible. This is usually done by altering the length of the connecting rod. If a greater change than this permits is found necessary, then new pistons must be made. This is a very frequent occurrence.

The Mean Effective Pressures given are for four stroke cycle engines at full power, using average Natural Gas or manufactured Illuminating Gas. This has a value of 87 B. T. U. for the Heat of Combustion per cu. ft. of Perfect Mixture. For any other gas, the values of M. E. P. given must be multiplied by the factors from the table below. These factors are found by dividing by 87 the figures from the last column of Table 3, page 50.

M. E. P. Factors.

Oil Gas	1.00
Uncarburetted Water Gas	1.00
Coke Oven Gas	0.93
Air Gas (Siemens Produce Gas)	0 79
Carburetted Water Gas	1.05
Anthracite Producer Gas	0.80
Bitumenous Producer Gas	0.87
Blast Furnace Gas	0.67
Acetylene Gas	1.28
Gasolene (liquid, vapor, or vaporized and mixed with air)	1.12
Kerosene (vaporized alone or mixed with air, and entering cylinder at about 150° F.)	0.90
Taylor Producer Gas (R. D. Wood Co.)	0.73

Owing to the great variation in circumstances, Table 4 can only be expected to give approximate results. However, fair results may be expected in average cases.

If the cylinder contents at the beginning of compression are highly heated or greatly diluted with air, the M. E. P. will be less than the values of Table 4. In general, actual values will be greater or less than the values of Table 4 if the design of the engine is better or worse than average.

A new table, similar to Table 4, can be arranged for a particular type or make of engine from actual experiment, so as to give much more accurate results. The methods of using the values of Table 4 to obtain power, cylinder size, etc., are given in Chapter X. Very often is is more convenient to use "equivalent mean effective pressure" or product of mechanical efficiency and m. e. p. rather than m. e. p. direct.

Calculation of Theoretical Efficiency.—It can be shown that the theoretical efficiency of our cycle depends on the ratio of the temperatures at the beginning and the end of compression, the expression for efficiency being

$$e = 1 - \frac{T_0}{T_1}.$$

The greater the compression pressure the greater the temperature range, as may be seen from the relation.

$$\frac{T_1}{T_0} = \left(\frac{p_1}{p_0}\right)^{\frac{n-1}{n}}$$

It must be noted that the theoretical efficiency depends on the temperature ratio only, and not upon the absolute magnitude of the temperatures. Hence an increase in the temperature at the beginning of compression, such as occurs in admission heating, serves no useful purpose. We may also see the same thing if we write the theoretical efficiency in the form

$$e = 1 - \left(\frac{v_1}{v_0}\right)^{n-1} = 1 - \left(\frac{c}{1 + c}\right)^{n-1}$$

The less the value of c the greater the value of e. Hence, the theoretical efficiency depends only upon the clearance and the index of the compression curve. If we know the compression pressure and the clearance of a given engine, we may safely calculate the theoretical efficiency as follows:

It has been shown by Professor Burstall that the gases in a gas engine cylinder do not greatly depart from the law $pv = RT$, even though they are so imperfect that the specific heat varies with the temperature. Hence we have

$$p_0 v_0 = RT_0 \text{ and } p_1 v_1 = RT \text{ hence}$$

$$\frac{p_0 v_0}{p_1 v_1} = \frac{T_0}{T_1}$$

We may therefore write the theoretical efficiency in the form

$$e = 1 - \frac{p_0 v_0}{p_1 v_1} = 1 - \frac{p_0}{p_1}\left(\frac{1+c}{c}\right)$$

Here is the efficiency we would obtain if we had no losses due to jacket water, friction, etc. It is the ratio of the work we would then obtain, to the lower heating value of the fuel used; p_0 and p_1 are the absolute pressures at the beginning of and the end of compression respectively, and c is the clearance expressed as a fraction of the displaced volume.

The actual efficiency of a gas engine is of course much less than the theoretical. In well designed engines of the small sizes, the actual efficiency is about 50% of the theoretical while with larger engines the percentage is greater.

Effect of Increase of Compression.—Theoretically the greater the compression pressure the greater the efficiency. We have also frequently referred to the fact that increase of compression makes ignition more certain. The surface exposed to the cooling action of the jacket water also decreases with increase of compression, since the clearance volume is decreased. This tends to decrease the jacket water loss.

However, there is a loss due to increase of compression which frequently counteracts all of the gains. Increase of pressure means increase of temperature at the end of compression, and since the heat added is unchanged the maximum temperature is increased. This means an increase in the loss to the jacket water and therefore a tendency to decrease the net efficiency.

These considerations seem to justify the observed facts, which are as follows:

If the compression pressure be increased there is a rapid increase in the efficiency up to a certain point, but when this point is reached there is little or no gain due to further increase in compression. The quantity of charge taken in per stroke is probably not affected by change in compression, and the power obtained from a given engine and a given size of cylinder varies in the same way as the efficiency. That is, increase of compression at first increases the power from a given cylinder, but after a certain point, further increase of compression does not increase the power, and in fact actually sometimes diminishes it.

Pre-ignition.—If the temperature at the end of admission is high the increase of temperature due to compression will heat the gases beyond their ignition point, and they will explode before the end of the compression stroke. This gives a card shown by the full lines in Fig. 5, whereas the card should have been as shown by the dotted lines. Evidently a considerable loss of area is sustained.

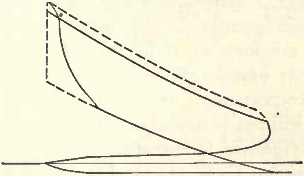


Fig. 5

Pre-ignition also causes considerable resistance to the forward motion of the crank, and may actually stop the engine. When it does not do this, it at least causes a loss of power, the amount depending on how early the ignition begins.

Sometimes compression ignites the charge at the proper time, and then the engine will continue to run at the full power if the ordinary ignition apparatus is cut off. This is called "self ignition" and is not in itself harmful. However, any slight overheating will advance the ignition point and develop pre-ignition, and then the power will diminish. Hence measures should be taken to prevent any possibility of self ignition. Sometimes, however, arrangements are made to use this self-ignition as the normal ignition. Then measures must be taken to cause it to occur exactly at the same time under all circumstances, or else the full efficiency will not be maintained.

The ignition temperature of the various gas engine fuels varies, that of gasoline being lowest. Then comes kerosene, crude oils, illuminating gas and blast furnace gas, in almost the order given.

In order to prevent pre-ignition either the admission temperature or the compression pressure must be kept down.

If the combustion chamber and the exhaust valve are well jacketed, the admission temperature will be low and then there is usually no trouble in preventing pre-ignition.

A possible exception may be made in the case of kerosene oil and crude oil. These must be initially heated in order to vaporize them, and on this account pre-ignition occurs at less compression pressure than we would otherwise like to carry.

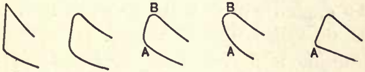
In most cases the combustion chamber is not sufficiently jacketed, and then, as the admission temperature is high, the compression pressure must be reduced. For average jacketing an engine operating on gasoline can carry a compression pressure of 60 pounds gage, on illuminating gas 70 pounds gage and on natural gas 90 pounds gage. Engines with poor jacketing must have less compression to avoid pre-ignition, while well jacketed engines may have greater compression, as has been stated. In very large engines the term "good jacketing" involves jacketing the piston.

On some engines a piece of metal of some kind projects into the combustion chamber entirely uncooled. This is the case frequently with the points of an electric igniter. A rib may also be placed where the jacket can not keep it cool. Such a piece of metal retains heat enough to cause pre-ignition with very low compression pressures. The remedy is to avoid ribs, sharp corners, etc. in the combustion chamber, and to keep the igniter points near and well connected with a thoroughly jacketed surface, so that heat is conducted from them readily.

CHAPTER VIII.

Combustion.

Explosion Line.—The pressure rises rapidly as the flame spreads through the mass. The increase is practically instantaneous in comparison with the piston speed with rich highly heated mixtures. The accompanying figures show the explosion line in various cases. Fig. 5 shows a rapid explosion and fig. 6 a slower one. Fig. 7 shows an explosion with a dilute mixture such as with producer gas, and Fig. 8 with a more dilute one such as blast furnace gas. In the two latter cases the ignition first



5 6 7 8 9

begins at A, but the flame has not completely spread through the mixture until B. There is a loss of area due to such slow ignition which can not be avoided. Of course the initial ignition must occur at the proper time in order that the card shall have a maximum area, and must be earlier as the mixture is more dilute. Fig. 9 shows the explosion line of a dilute mixture with late explosion. The ignition begins at A. This would be early enough and would give a good line if the mixture were rich. Ignition should occur at 98% of the compression stroke for a rich mixture, and as early as 70% for a very weak mixture.

When an engine is first designed the time of ignition should be provisionally but not definitely fixed. Then it may be set with an indicator when the engine is first run. If this is not convenient, the best setting may be found by observing when the engine will pull the greatest load as the time the ignition is varied. It is always desirable to provide some means of varying the ignition through a slight range while the engine is running, in order to set it exactly.

When a weak mixture is normally used and the ignition is early, the engine is likely to reverse its direction of rotation if moving very slowly as in starting. For this reason it is desirable to have some means of making ignition occur on or slightly beyond the center in starting. The ignition apparatus is shifted to give the proper lead after full speed is reached.

Suppression of Heat.—Suppose the maximum pressure of a good gas engine card is measured, and the temperature computed from the quantity of charge within the cylinder assuming the law $pv = RT$. We may also calculate the compression temperature in the same way. From these two temperatures we may calculate the amount of heat added by the explosion, if we assume value for the specific heat at constant volume.

If we assume that the specific heat is constant for all temperatures, the result of the computation will show that the heat added to the working substance by the explosion is only about one-half of the heat known to be liberated from the quantity of fuel burned. The other half of the heat of combustion of the fuel has seemingly disappeared. This phenomenon is known as "heat suppression."

Theories of Heat Suppression.—Some of the heat of combustion is, of course, added to the jacket water while the inflammation is going on, and this accounts for some of the suppressed heat. This is only a very small portion however, as the time between beginning of ignition and maximum pressure is exceedingly small. If any large amount of heat passed out during this time, the whole heat suppressed would vary with the amount of exposed surface. This is not found to be the case, as the same fraction of the heat is suppressed regardless of the amount of surface exposed to cooling action.

The original theory proposed by Hirn was that the heat passed into the first layers of the cylinder walls and was afterwards restored to the gas, when it expanded and became cooler. This was called "wall" action and was supposed to be similar to the wall action in steam engines. This theory is refuted by the fact that the heat suppression is independent of the wall surface. There may be some wall action, but it can account for but a small portion of the suppressed heat.

The "dissociation" theory, proposed by Clerk, was that as CO_2 and H_2O were decomposed at high temperatures—the fuel and oxygen would not ignite after a certain temperature was reached. A considerable part of the fuel would burn, but when the dissociation temperature was reached, the balance would wait until the temperature began to be reduced by expansion. It is now known that the dissociation temperatures are never reached in a gas engine, so that although the action is possible if the temperature is high enough, it never occurs in an engine cylinder.

The "after burning" theory is that the combustion is not complete at the instant of maximum pressure. The inflammation has spread throughout the mass when the maximum pressure is reached, but there still remains everywhere a percentage of unburned gas. That is to say, the gas at any point starts to burn, but before the combustion is complete at that point the inflammation has passed to the next point. The whole mass has been inflamed when maximum pressure is attained, but the gas is still burning, and continues to burn during expansion.

This theory is held by many at the present time, but the best authorities have abandoned it, and combustion is believed to be complete at the instant maximum pressure is reached in most cases.

The theory now generally held is that there is no heat suppression at all, but that the specific heat increases with the temperature. Some heat passes into the walls and jacket water, and the balance goes to heating the working substance. As the actual specific heat is much higher than the constant value formerly assumed, the maximum pressure, and consequently the maximum temperature, are lower than the calculated values.

Jacket Loss During Explosion. — Even though the inflammation is practically instantaneous there is some loss of heat to the cylinder walls during this time. For this reason the surface of the clearance space or the "combustion chamber" should be as small as possible. The volume is, of course, fixed in order to secure the desired compression pressure. However, the surface may be varied considerably. If the valves are contained in small pockets with narrow passages leading to the main clearance space, the surface is much larger than when there is a single large chamber into which the valves open directly. Heat is also lost through the combustion chamber walls during expansion, which effect we will consider later.

When the mixture is dilute and the time of inflammation is increased, the jacket water loss, during inflammation, is increased. However, the time of expansion is diminished, so that the total jacket water loss is not materially changed.

Effect of Dilution.—The working substance is composed of fuel, oxygen, nitrogen and products of previous combustion remaining in the clearance space. The composition cuts no figure as we are merely concerned with the fact that a certain amount of heat is added to the working substance.

The less the amount of heat the lower the final temperature. We have already seen that this temperature has no effect on the efficiency, however. The same fraction of the heat added is turned into work regardless of the dilution of the charge. Hence there is no loss due to heating up the nitrogen and other dilutants, although such loss is often ignorantly referred to. The greater the dilution the less the maximum temperature and less the loss due to jacket water for a given surface. However, dilution increases the size and consequently the surface of the cylinder for a given power, and this tends to increase the jacket loss. With slight dilution the first effect predominates and the efficiency increases, but as the dilution becomes greater the efficiency begins to diminish. Of course the power of a given size of cylinder always decreases with the dilution.

For this reason an engine is usually run with nearly as perfect a mixture as it is possible to obtain. Of course, nitrogen and products of combustion always give some dilution, and producer gas and the like contain further dilutants.

As has been already stated, in order to be sure that there is no excess of gas, which would be very wasteful, a slight excess of air is always maintained. When economy is more important than maximum power a further excess of air is used to increase the efficiency by the slight dilution already referred to.

Maximum Pressure.—All of this theory is of little use to the designer, as it gives no means of computing the maximum pressure in any given case. We must, therefore, use empirical data.

It is impossible to formulate any definite rule, as circumstances vary so greatly. Two engines under similar conditions will give similar cards, except that one may have a sharp peak and the other a round corner at the point of maximum pressure. The maximum pressure will therefore be very different in the two cases. Often the sharp peak seems to be wholly the result of indicator inertia. A slight increase in the excess of air will increase the time of inflammation, and this will also cause a sharp corner, while the total area of the card will remain unchanged.

The larger the charge the greater the maximum pressure, so that the admission temperature has an important effect.

Increasing the amount of jacket water increases the maximum pressure, as the admission temperature decreases.

The maximum pressure varies from 200 to 350 per sq. inch gage. A pressure of 200 occurs with low compression and weak mixtures. Ordinary compression, say about 70 to 80 pounds gage, gives a maximum pressure of from 250 to 300 with ordinary illuminating gas or natural gas. Higher compression or richer mixtures give values up to 350. The values given are those occurring in ordinary working. Higher values can occasionally be reached. Thus when a hit or miss engine is running light, the cylinder is quite cool after several misses, and the next charge taken in will therefore be at a low temperature and consequently larger. The maximum pressure is therefore larger.

An engine is frequently started with a charge of compressed air and gasoline. Such a charge fills all of the compression space, there being no burnt products as in the regular charges; the temperature is also lower than that of the regular charges. Hence the amount of the charge is very much greater, and the maximum pressure correspondingly higher than in ordinary running. When the air pressure is higher than the normal compression pressure, and a good mixture happens to be ignited with the engine exactly on the center, a wreck sometimes occurs.

To provide for such contingencies a gas engine should be designed for a maximum pressure of at least 300 lbs. per sq. in. Some builders even go up as high as 600. The value of the maximum pressure is used in calculating the thickness of the cylinder walls, size of connecting rod and torque on crank shaft.

Mixing the Charge.—It is now generally believed that no matter how irregularly the charge is introduced into the cylinder, the internal currents due to convection, to the entrance of the gases, and to the motion of the piston during admission and compression, will cause a thorough mixture of the fuel and air by the time compression is completed. Hence no attention need be paid to this point in four cycle engines of the usual construction.

CHAPTER IX.

Expansion and Selection of Speed.

Expansion Index.—Examination of the expansion curve of a gas engine shows that it usually rises above an adiabatic drawn on the assumption that the products of combustion act as a perfect gas. Such an adiabatic would have an index of about 1.37, while the index of the expansion curve averages 1.3. The expansion curve is thus higher than the adiabatic, and this seems to indicate the addition of heat during expansion. However, the variable specific heat assumption gives an adiabatic much less steep than the perfect gas adiabatic, and the expansion curve is then found to always lie below. Hence it appears that heat is always lost to the cylinder walls during expansion.

The larger the engine the less the heat lost to the walls, as we will see later. The less the heat loss the less the index of the expansion curve. Hence the index for very large engines is about 1.2, for medium sizes 1.3, and for very small sizes it often reaches as much as 1.5. The value of 1.2 gives a curve lying very much above the perfect gas adiabatic; but nevertheless the curve probably lies below the true adiabatic for an imperfect gas.

Jacket Water Loss.—In order to keep the wearing surfaces of the cylinder at a temperature which will permit lubrication we are compelled to surround the walls with a jacket. We have also found it necessary to cool the combustion chamber surfaces where no wear occurs in order to increase the size of the charge and to permit of high compression pressures. As the jacket therefore keeps the walls at a low temperature, compared with the temperatures of the working substance, a passage of heat occurs from the charge to the walls and from the walls to the jacket water. This begins at the instant of ignition and continues throughout expansion. It is surprising that the loss is not more than it is. The gases within the cylinder are at a white heat on the average, and yet the surrounding walls can be kept cool enough for lubrication without extracting an undue amount of heat from the charge. The reason is found in the fact that gases conduct heat very poorly. This alone is the cause of the success of the gas engine and abandonment of the air engine, which offered nearly equal theoretical possibilities. The poor conducting power of the charge prevents its being readily heated by outside agents in the air engine and keeps the heat of combustion from being lost in the gas engine.

However, the jacket loss is bad enough and we must of course seek to diminish it as much as possible. This loss is the main reason why the actual efficiency of the gas engine is only about 50% of the theoretical. The jacket loss depends directly on the temperature difference, the exposed surface and the time of exposure. We have already considered the temperature effects in the previous chapters of this section.

Cooling Surface.—The exposed surface should be a minimum, but as the surface is increasing during expansion it is hard to say just what this condition would lead to. We have a given volume at the beginning of ignition and another at the end of expansion, and desire to arrange the surface enclosing these volumes to the best effect.

One theory in this connection is as follows: As the temperature difference is greatest during the early part of expansion the exposed surface should be a minimum at some point in the early part of the stroke. If this be worked out mathematically, making various assumptions, it comes out that the stroke should be $1\frac{1}{2}$ times the diameter. Then, assuming the greatest possible piston speed which will make the wear a reasonable amount, the rotative speed is fixed.

Another theory is that the total time during which the hot charge is exposed to the cooling action should be a minimum. Then the rotative speed should be as great as possible without giving undue inertia effects. A high rotative speed and a reasonable piston speed means a short stroke. Accordingly the advocates of this theory recommend that the stroke be made equal to the diameter. Still other builders make the stroke twice the diameter, or greater. On the whole we may conclude that the ratio of stroke to diameter does not exercise any very great effect upon the cooling surface. This ratio may therefore be determined by considering the question of rotative and piston speed. However, the proportions should not be extreme and the ratio of length to diameter should be between 1 and 2.

Change of Cooling Surface with Size.—The greater the total volume of a cylinder of a given kind the less the cooling surface. Hence we should expect that as the power of gas engines increase, the percentage of jacket loss will diminish. This is borne out in practice, and the larger the size of an engine the less the proportionate loss due to jacketing.

Effect of Speed on Jacket Loss.—The less the time of exposure to cooling action the less the jacket loss, for evident reasons. Hence if the rotative speed of a given engine be increased the jacket loss will diminish. Of course the inlet and exhaust ports must be large enough for the increased speed, or other effects will enter. In a general way we should make the piston speed as great as possible, but whether the jacket loss is decreased by high rotative speed and short stroke, or low rotative speed and long stroke, does not seem to be known.

Selection of Speed.—It appears, therefore, that we have not found a good basis for selecting the relative values of the stroke and the diameter, piston and rotative speed from our consideration of the jacket loss. Therefore in default of a better method we may proceed as follows:

A piston speed of 600 ft. per minute is found to give good results in average cases, being fast enough to avoid bulky engines, and slow enough not to cause undue wear of piston and cylinder. However, 600 ft. per min. piston speed gives very high rotative speeds for small engines, and we may therefore go as low as 400 ft. On the other hand 600 ft. gives very slow rotative speeds for large engines, and we may therefore go to 800. Some very large engines go as high as 1000 ft. per minute.

A more rational method of procedure, giving practically the same results, is as follows.

It may be shown that engines are alike so far as vibration and pounding are concerned, if the "Initial Inertia Pressure" is the same. This is the average of the two values at the ends of the stroke of the pressure in pounds per square inch of piston corresponding to the inertia of the reciprocating parts. It is given by $I = .00001421\, wl\, N^2$ where w is the weight of reciprocating parts per square inch of piston, N is the number of revolutions per minute, and l is the length of stroke in inches. This reduces to $N = 265 \sqrt{\frac{I}{wl}}$.

w is about 1.7 for the usual type of single acting trunk piston engine, a safe value of I is about 15.4 pounds per square inch. Then $N = 800/\sqrt{l}$ is a safe rational rotative speed. This corresponds to a piston speed of $133\sqrt{l}$, which will be found to agree with the above values.

CHAPTER X.

Power and Efficiency.

Mean Effective Pressure.— The various circumstances we have been considering are so complicated that it has not been found possible to predict the power of an engine on a rational basis. We, therefore, resort to empirical data. A table has been prepared giving results of a large number of gas engine tests, and from it a set of average values have been selected. The following facts have appeared:

A given mixture of gas and air will give a certain mean effective pressure which varies with the compression pressure and with the size of the engine. The higher the compression the greater the M. E. P. up to a certain point. Beyond this point increased compression has little effect on the M. E. P. The M. E. P. increases with the size of the cylinder and hence with the total power developed.

The M. E. P. also increases with the heat developed per cubic foot of perfect mixture. In a general way, the M. E. P. increases directly with the heating value, but this does not always hold true. Table 4 has been prepared from the data obtained and it gives the probable value of the M. E. P. under various circumstances.

Mechanical Efficiency.—The value of the M. E. P. gives us a means of finding the indicated horse power. However, we usually design an engine for a given brake horse power, and hence should know the probable mechanical efficiency, which is the ratio of the two.

Good engines have a mechanical efficiency of 85 to 90% when on full load, while poorer engines may go as low as 70%. A safe assumption for ordinary engines is 80%.

Size of Cylinder.—In order to design a cylinder for a given indicated horse power we proceed as follows:

We first decide the compression pressure. We may then select the M. E. P. from table 4. We decide the piston speed and then calculate the cylinder dimensions as follows: We have in general

$$\text{I H P} = \frac{(\text{M. E. P.})\ L.a.x.}{33000}$$

where L is the stroke in feet, a the area in square inches, and x the explosions per minute, which is ½ the number of revolutions in a four cycle engine at maximum power. If s is the piston speed we have

$$s = 4.\ L.\ x \text{ or } Lx = s/4.$$

If d is the diameter in inches $a = \pi/4 \times d^2$, and hence we have, I.H.P.=

$$\frac{(\text{M. E. P.}) \times d^2 \times s \times \pi}{33000 \times 4 \times 4} = \frac{(\text{M. E. P.}) \times d^2 \times s}{168100}$$

Therefore diam. of cyl.

$$= d = 410 \sqrt{\frac{\text{I. H. P.}}{\text{M. E. P.} \times \text{piston speed.}}}$$

We may then decide the length of stroke as about 1½ times the diameter, and calculate the rotative speed from this and the piston speed. In deciding the piston speed and the ratio of stoke to diameter we may, of course, vary the values to suit any individual case.

Another method is to use the rational

rule of page 117; *r.p. m.*$=800/\sqrt{l}$.

This gives

$$d = 35.5\sqrt{\frac{\text{I. H. P.}}{\text{M. E. P.}}} \cdot \sqrt{l}$$

A provisional value of l is to be guessed at, and the corresponding value of d found, and then a final value of l taken about $1\frac{1}{2}$ times the value of d and a final value of d found.

The data here given are on the basis of the maximum possible power that can be developed. The power which the engine is to develop under working load should, of course, be somewhat less than the maximum power.

It is customary to rate an engine at about $^8/_9$ of the maximum power. That is to say, the engine should be capable of about $12\frac{1}{2}\%$ overload.

Efficiency.—The net efficiency of an engine is usually considered as the ratio of the work obtained at the brake to the mechanical equivalent of the heat supplied, using the lower heating value.

There are 2545 B.T.U. in a horse power hour, so that 2545 times the brake horse power, divided by the heat of the fuel supplied per hour, gives the net efficiency.

The efficiency, of course, varies with the size of the engine compression pressure, richness of the fuel, and other circumstances. In small engines it is as low as 16% and in large engines it sometimes reaches 30%.

The average value for a good engine is 20 to 25%.

Fuel Consumption.—If we assume the probable efficiency of an engine we may readily calculate the fuel consumption. We first find the heat required per horse power hour by dividing the quantity 2545 by the assumed efficiency. Thus an efficiency of 22% signifies that the fuel supplied per hour has a heating value of $2545 \div 0.22 = 11{,}500$ B. T. U. per horse power. This is often given as a fair consumption. From this value and the heating value of the fuel used we may calculate the actual fuel consumption in an average case. This corresponds to 18 cu. ft. per horse power hour for average illuminating gas, or one-tenth of a gallon of gasoline.

These are, of course, values for good engines of fair size. In many cases the fuel consumption is a great deal higher.

Consumption of Jacket Water.—In the averge case about 50% of the heat supplied goes to the jacket water. It is found that the cylinder walls will be maintained at the proper temperature if the discharge jacket water is about 150°. The initial temperature averages about 60°, so that the water absorbs 90 B. T. U. per pound. We therefore require about $11{,}500 \div (2 \times 90) = 64$ lbs. or 7.5 gallons of water per horse power hour. These figures are, of course, for a system with a continuous supply of jacket water which goes to waste after use. For systems in which the same water is cooled and used over again the figures will vary. Where a single cylindrical cooling tank is used, which may be done for small and medium powers, there should be a capacity of about 40 gallons per horse power, in order to afford sufficient cooling surface.

CHAPTER XI.

Methods of Governing.

Classification of Governing Methods.—The systems at present in use in four cycle engines are as follows. Hit and miss, which regulate the number of explosions; throttling, which regulates the quantity of air and gas by reducing the admission pressure; variable admission, which regulates the quantity of air and gas by reducing the time of admission; and variable fuel, which regulates the fuel supply only.

Hit or Miss Governing.—This is the method most in use. It operates very successfully, the only disadvantage being the great weight of fly wheel required. When the engine is running light each explosion is followed by several idle cycles, and the fly wheel must be large enough to keep the speed up during this time.

The governor works by cutting off the supply of fuel in some way. In some cases a fuel valve opening into the air pipe is opened or not as the governor dictates

When the fuel is cut out, the air alone is admitted and compressed and afterward expanded during the working stroke, and exhausted.

The admission of these cool charges of air, and the continued action of the jacket water, cools the cylinder down considerably. Hence a charge taken in after a missed cycle is greater than a charge after an explosion. When the engine is running so as to explode several times and then miss, the card after each miss will be largest, and the successive cards will decrease regularly as the cylinder gets hotter. This action, of course, slightly increases the irregularity of hit or miss governing.

When a cycle is missed there is an area between the admission and exhaust line which represents work done in taking in and exhausting the air. Except for this loss, a hit or miss engine works at full efficiency on light loads, which is a great advantage. It may be remarked that the exhaust line after a missed cycle is always much higher than after an explosion, owing to the absence of the scavenging action before referred to.

Another style of hit or miss governing operates by holding the exhaust valve open during the admission stroke. An automatic inlet valve is also used which does not open as the exhaust passes back into the cylinder. Instead of compressing, the exhaust is discharged into the exhaust pipe again. This is claimed as an advantage, but it does not compensate for the disadvantage of an automatic inlet valve.

Throttling Governing.—This system uses a throttle valve actuated by the governor and placed in the air and fuel pipes. The friction so caused lowers the admission line, and consequently the amount of the charge admitted. The valve is so arranged as to keep the proportions constant however. As the initial pressure is reduced the compression will fall, since the clearance fixes the ratio of admission and compression pressures. The throttling also causes a slight loss, owing to the lowering of the admission line. Hence throttling decreases the efficiency as the load decreases, principally owing to the decrease of compression pressure. However, very good regulation can be secured with comparatively light fly-wheels, and this is the merit of the system.

Variable Admission. — A few engines regulate the quantity of air and fuel by cutting off the time of opening the admission valve or holding it open during part of the compression stroke. This gives the same result as the preceding system. The efficiency decreases with the decrease of compression pressure on light loads. There is a very slight gain in this system over the preceding one, owing to the absence of the throttling loss.

Variable Fuel.—In this system there is an inlet valve admitting air into the cylinder, and a fuel valve opening into the air pipe just before the inlet valve. The governor dictates the time during which the fuel valve is open. The quantity of fuel is then regulated, the air remaining constant. As a mixture will not explode when the proportion of air is too great, this system will not operate on very light loads. Accordingly instead of permitting very short openings, the fuel valve is not opened at all after a certain point is reached. The system then becomes hit or miss.

This system gives the best results of any when the load is nearly uniform or when light loads rarely occur.

Miscellaneous Systems of Governing. — There are other systems in use, but none of them have attained very much success. There are also a number of systems of cutting down the power of an engine without changing the fuel consumption at all. This can not be called governing however. One such system is the shifting of the time of ignition, so that the area of the card is varied. This is often used in automobile engines where fuel consumption is not material.

It is also possible to build an engine with such small inlet and exhaust ports that a slight increase of the speed will cause a great reduction in the charge and decrease of card area. Such engines require no governor at all. When the load is thrown off the engine speeds up a little but can not run away. Of course such a system is very wasteful and requires a large engine for a given power.

CHAPTER XII

Cylinder Action in Two Cycle Engines.

Description of a Two Cycle Engine.—An explosion of about half the value of that of a four cycle is obtained every revolution. The space surrounding the lower side of the piston and enclosing the connecting rod and crank is made air tight. A check valve opening inwards admits the mixed charge to this space when the piston is making the up stroke. On the next down stroke the charge is slightly compressed in the large clearance space afforded by the crank case. When the piston has nearly reached the lower end of the stroke a port in the side of the cylinder is opened and the exhaust from the previous explosion passes out. As the piston moves slightly farther, a passage connecting the cylinder with the crank case is opened through a port in the side of the cylinder, and the slightly compressed charge in the crank case passes into the cylinder, displacing the exhaust in so doing. The piston then returns and the charge is compressed, exploded and expanded just as in the regular Otto cycle. The method of executing the cycle is slightly different however. The idle admission and exhaust strokes are dispensed with and another method of substituting the fresh charge for the burnt gases is used. Sometimes, instead of using a port in the side of the cylinder for admission, a check valve at the top of the cylinder is used. In other cases, instead of using a check valve for admitting the charge into the crank case, a port in the side of the cylinder is uncovered by the piston at the upper limit of the stroke. This gives an engine without a valve of any kind.

Thermodynamically the cycle is the same as the Otto.

Disadvantages of the Two Cycle Engine.—The charge compressed in the crank case theoretically expands to exactly its original volume after passing into the cylinder, when the piston is at the lower end of the stroke. Hence the pressure throughout the system would be exactly atmospheric if there were no friction losses in passing through the various ports and pipes.

Owing to these losses a complete cylinderfull of fresh charge does not pass into the cylinder, but a large amount of the exhaust remains instead.

It is often supposed there is danger that the fresh charge will escape from the exhaust pipe. There is no possibility of this however, as enough fresh charge never enters the cylinder to even reach the vicinity of the exhaust pipe.

That these statements are true is shown by the fact that the M. E. P. in a two cycle engine never exceeds 30 per sq. in., and usually falls below this. The M. E. P. in a four cycle engine averages 75 per sq. inch. This shows that less than half of a cylinder full of fresh charge is forced into the cylinder.

Hence doubling the number of explosions does not make up for the small size of the charge, and a two cycle engine has a larger cylinder than a four cycle for the same power.

Displacer Two Cycle Engines.—By providing a separate "displacer" cylinder of greater capacity than the working cylinder to initially compress the charge, instead of using the crank case a greater amount of charge can be forced into the cylinder. By this means a mean effective pressure of 65 has been obtained, so that the engine would give nearly twice as much power as a similar size four cycle.

CHAPTER XIII.

Details of Design.

Stresses of an Engine Frame.—We will use the term "frame" to designate that part of the gas engine which connects the cylinder casting with the crankshaft bearings. The "bed" is that part which holds the main bearings to the foundation. In horizontal engines the frame usually carries the crankshaft bearings as part of the same castings. Often the frame rests directly on the foundations, and it is then the bed also. In a vertical engine the frame and bed are usually distinct, the latter carrying the main bearings.

The pressure of the charge in the cylinder acts on the piston, and this force is transmitted by the connecting rod and crank, so that there is a force exerted by the crankshaft on the main bearings, exactly equal to the pressure on the piston. There is also an opposite force acting on the cylinder head, of the same amount, due to the unbalanced cylinder area acted upon by the pressure of the charge.

There is therefore a tendency to separate the cylinder and the main bearings from each other, and the office of the frame is to hold them together.

That is to say, there are applied to the frame at the point where the cylinder is attached, and at the main bearings, equal and opposite forces exactly equal to the load on the piston. These forces are horizontal in a horizontal engine and vertical in a vertical engine.

The maximum value of this force, which of course the frame must be designed to carry, is the load on the piston due to the maximum pressure, which is probably 300 to 600 pounds per square inch. Besides this, there are forces due to the obliquity of the connecting rod, acting in one direction on the cylinder, and in the other on the main bearings.

When a horizontal engine runs over, these forces act downwards on the piston and upward on the main bearings. They constitute a pure couple, tending to rotate the whole engine in a direction opposite to the direction of rotation. This couple is not very important except in vertical engines, where it tends to tip the engine.

In addition there is a force exerted by the crankshaft on the main bearings, due to the unbalanced action of the reciprocating parts. The resultant action is a force of varying magnitude. This will tend to sway the main bearing back and forth, or up and down, or a little of both, according to the amount of the counterbalance. We will discuss this in detail at a later period.

There is also a force due to the belt pull or the like in all but direct connected engines. The "unbalanced action" force and the belt pull must be transmitted by the frame or bed plate to the earth.

The variation in direction and magnitude of the "unbalanced action" force tends to cause vibration of the main bearings, and this is the reason why heavy foundations must be used. The action is, of course, identical with that in a steam engine. The explosion has no tendency whatever to cause vibration except in the case where the frame is not stiff enough and the cylinder and main bearings separate slightly with each explosion. This action can be distinctly felt in a poorly designed engine. The forces acting on the bed and frame are then as follows:

A force tending to separate the cylinder from the main bearings acting in a straight line between them, and due to the pressure in the cylinder.

A couple tending to rotate the whole engine opposite to the direction of rotation, due to the connecting rod thrust.

An "unbalanced action" force tending to sway the main bearings back and forth or up and down.

A belt pull or the like tending to tip the main bearing.

The three latter forces are resisted by the action of the foundation or the weight of the engine and foundation.

Engines are very often designed with little knowledge of the stresses we have been considering. The metal is distributed in a poor way, so that a much greater quantity than necessary must be used.

Great weight is necessary to decrease vibration, but it is much more economical to have a heavy foundation than a heavy engine.

The "Straight Line" steam engine, designed by Professor Sweet, is a good example of what a steam or gas engine frame should be. In this engine a straight frame connects the cylinder and bearings, and the bearings are mounted on a pedestal to resist the unbalanced action and belt pull.

The method of placing the fly-wheel between the main bearings reduces the load on the crankshaft.

In a horizontal engine the average resultant load on the main bearings due to the piston pressure and the weight of the fly-wheel, acts almost at an angle of 45 degrees to the horizontal. Hence, all the wear can be taken up and the bearings reduced to a true circle by simply closing down on the caps, if the bearings are split at this angle. If the bearings are split horizontally, the horizontal pressure of the crankshaft causes wear which can not be wholly taken up by closing down on the box. That is to say, after such adjustment the bearing will not be perfectly round, and the shaft will not have proper bearing surface. Accordingly horizontal engines with horizontally split boxes should have these boxes made in the style of the quarter box, in order to allow for adjustment in the direction of wear.

In vertical engines the whole wear is downward, and hence the bearings should be split horizontally. Quarter blocks are not necessary. Caps are kept in line by dovetails fitting in the bottom half, or by making the bolts a tight fit in the holes.

Types of Horizontal Engine Beds.— In most small horizontal engines, and some large ones, the cylinder and bed are in one piece. The disadvantages of this plan for large engines are as follows: If the water jacket freezes and bursts, as sometimes occurs, the expense of renewal is great, and the cylinder cannot be removed and sent to the factory for reboring when necessary. However, the principal difficulty is the trouble in casting such a complicated piece in large sizes. There is little difficulty with smaller sizes, and hence, owing to the machining saved, a one-piece engine is the cheapest type.

When the cylinders and bed are separate there are two common methods of fastening them together. In the first, two horizontal lugs on the cylinder are bolted to the top of the bed, while in the second method, a circular flange on the cylinder is bolted to a similar flange on the frame.

Cylinder Details.—The cylinder is usually provided with a jacket for slightly more than the length uncovered by the piston. In order to provide sufficient bearing surface for the piston, the internal shell is carried out somewhat farther. When the piston is on the forward center it projects somewhat from the end of the cylinder, as little bearing surface is needed at that time.

The cylinder is usually open at the end away from the crank and covered by a cylinder head. However, when the piston can be withdrawn from the crank end of the cylinder, as is the case in most horizontal engines, the other end is sometimes solid, to avoid joints.

The coring of the jacket space is the principal feature of a gas engine cylinder.

The jackets have openings at one end of the cylinder and similar openings in the head allow free circulation of water through this part. Bridges across the jacket space are provided for at points where lubricators or relief cocks are placed, in order that holes drilled at these points may reach the internal shell without coming in contact with the jacket water.

The cylinder is usually counterbored just beyond the limit of the last ring, so that the ring will not wear a shoulder.

The cylinder head is usually plain, the valves, etc., being on the cylinder. This is the best plan, as then the head can be easily removed to pack the joint, as this joint is often troublesome and water leaks into the cylinder or outside, or, worst of all, the explosion leaks into the jacket. There should be no narrow places in the gasket, all holes being kept well away from the outer edges.

Piston and Rings.—The piston itself is a loose fit in the cylinder and leakage is prevented by piston rings. The back of the piston gets very hot when the engine is running, while the jacket keeps the cylin der comparatively cool. Hence, in order to secure a working fit, the piston must be turned about .004″ per inch of diameter smaller than the cylinder bore. Large pistons have the end water jacketed by means of a swinging pipe.

The rings are made of cast iron and turned to a diameter larger than the cylinder bore. A small section is then sawed out so that the rings will enter the cylinder. They are pressed against the sides of the cylinder by their tending to resume their original diameter.

Some makers clamp their rings in their final position and turn them to a true circle, so that they will press uniformly against the cylinder. However, better results are accomplished by boring the rings eccentric, so that they are thin at the split and thick opposite. Four rings are usually used. Fewer gives a poor joint and more a slightly better one. The rings should be placed between the wrist pin and the end. Rings placed in front of the wrist pin are of doubtful utility. They should be held so as to break joints, by means of dowel pins. Usually the places for the dowel pins are filed in the split rather than drilled in the ring.

Piston Pin.—The piston pin or "wrist pin" is held by lugs on the inside of the piston, with a space between for the connecting rod. Usually the pin is kept from rotating by putting set screws through the lugs. Another construction is where the pin is fixed to the rod and rotates in bushings fastened to the piston. The joint is then lubricated by oil scraped from the side of the cylinder. When the pin is stationary it is oiled by a tube leading from a hole in the piston. The piston pin is usually a straight bar of cold rolled steel.

Connecting Rods.—In order to reduce the pressure on the cylinder due to the obliquity of action of the rod, to a reasonable amount, the length of the connecting rod should be from 2½ to 3 times the stroke. The longer the rod the less the pressure.

During the greater part of the time the pressure on the piston tends to compress the connecting rod. However, during the latter part of exhaust and the early part of admission, the inertia of the reciprocating parts causes a tension on the rod. In a high speed engine with heavy reciprocating parts and low compression, the inertia force is sometimes greater than the compression force during the latter part of compression. Hence there may be tension on the rod for a short time just before the end of compression, in vertical as well as in horizontal engines. Therefore, during most of the time there is pressure on the cylinder side of the wrist pin and crank pin, but during some periods the pressure is on the other side. There is, therefore, a tendency for the wrist and crank bearings to knock, if there is any lost motion.

In high speed engines with low compression, where the inertia force becomes greater than the compression force near the end of compression, as we have stated, if there is a slight pre-ignition, the stress on the connecting rod changes very suddenly from tension to compression, and a very pronounced knock occurs, even if there is very slight lost motion. This has a characteristic metallic ring and is a sure sign of pre-ignition. As the pressure is sometimes on one side of the crank and wrist pins, and sometimes on the other side, the rod must be designed to resist tension forces applied at the outer end. It is often stated that the rods of single acting engines are always in compression, hence there is never any load on the bolts or straps holding the halves of the two boxes together. This statement is made without considering the effect of the inertia of the reciprocating parts, and is, of course, fallacious.

However, there is not any great force tending to separate the halves of the bearings from each other, and hence they do not have to be tied together so strongly as in the case of steam engines.

The rod rotates on the wrist pin through a very small angle, so that the wear on the wrist pin is not very great. In horizontal engines the wear is taken up by reaching into the piston from the front. In some enclosed case vertical engines the piston and rod must be withdrawn to take up the wear.

The crank box has much greater wear and must be comparatively easy to adjust. In enclosed cases a cover plate of some kind must be removed for this purpose.

Counterbalancing.—The crank pin, crank box and other rotating parts must be counterbalanced, as well as part of the reciprocating parts. If the rotating parts only are balanced, there is an unbalanced force due to the reciprocating parts, in the direction of the axis of the cylinder, tending to sway the main bearing. If the reciprocating parts are balanced fully there is an unbalanced force at right angles to the axis, due to the unbalanced centrifugal force of the extra counterbalance. Hence it is customary to balance all of the rotating parts and some fraction of the reciprocating parts, usually from $\frac{1}{4}$ to $\frac{3}{4}$.

In a horizontal engine an unbalanced force at right angles to the axis is easily taken care of by the foundation, and hence the reciprocating parts can be nearly balanced, while in a vertical engine unbalanced forces in the direction of the axis are easily taken care of, and hence the reciprocating parts are only slightly balanced.

In order to relieve the crank shaft from stresses due to transmission of the unbalanced forces, the counterbalances should be fastened directly in the crank. However, cheap engines have the counterbalance cast in the fly-wheel.

Choice of Fly-wheels.—The fly-wheel is the leading feature of the gas-engine. A four cylinder engine using throttling governing would be required to secure as steady a turning moment as a steam engine with a single cylinder. Four cylinders cause great complication, and throttling governing is not always desirable, so that resource is had to heavy fly-wheels.

By using a single heavy enough wheel,

a hit or miss engine, which at light loads has one power stroke to eleven idle ones, will give good results in electric lighting service. This is one extreme, while an engine with three cylinders, throttling governing and two small fly-wheels is the other. The designer must choose between these extremes, and the choice is often difficult.

English practice inclines to two cylinders, hit or miss governing and comparatively heavy fly-wheels for electric lighting; while American practice inclines to three cylinders, throttling governing and light wheels.

For engines for ordinary power purposes, a single cylinder is usually used. Two fly-wheels are used, one on either side of the engine. This is the typical arrangement of small and medium engines.

With large fly-wheels, as in the case of very large engines, or smaller engines with large wheels, the overhanging weight causes too great a load on the crankshaft, and there must be a bearing on each side of the fly-wheel. Small wheels have a solid hub, and wheels up to six feet in diameter may be made in this way. In order to remove strains in casting, and also to facilitate the placing of the wheels upon the shaft, a split hub is used with large wheels. It is good practice to make wheels four feet in diameter and over, with split hubs. The hub should be split on both sides of the shaft in order to properly relieve the casting strains. Sometimes casting strains are eliminated by the use of curved arms.

When the counterbalance is placed on the cranks, as has previously been stated to be the best practice, the fly-wheels should be carefully balanced. Sometimes cored slots are left which are filled with lead in the proper place in order to effect the balancing.

Crank Shafts.—The almost universal practice is to use forged steel crank-shafts. These are usually forged solid in the space between the crank throws, requiring the the removal of considerable metal by machining of some kind.

Steel castings are occasionally used fo

crank shafts, but the practice is not in good repute, on account of prevalance of blow-holes and shrink-holes. However, these faults may be eliminated by care, and then a steel-casting is perfectly proper.

Engine Types.—In the discussion of details an engine with a single-acting trunk piston has been assumed. This is by far the most prevalent type. Both single-acting and double-acting engines with piston-rods and crossheads are sometimes used. Discussion of such types is omitted for lack of space.

Engines with more than one cylinder sometimes have them in tandem. However the usual arrangement is with cylinders side by side. Sometimes multi-cylinder horizontal engines have some cylinders "opposed," that is with open ends facing each other. The arrangement and number of cylinders affects the vibration, but we have not space to discuss the subject.

Starting.—A gas engine cannot usually be started with load on, so that some provision must be for unloading, either by taking the load off the driven apparatus, use of a friction clutch, etc.

Small gas engines are started by being rotated by hand until an explosion is obtained. Engines connected to an electric dynamo are started by supplying electric current and running the dynamo as a motor. The general method, however, is the use of compressed air in some form or other.

For an engine with two or more cylinders the most reliable method is the operation of one cylinder as a compressed air engine by use of special valves, while explosions are being started in the other cylinder. A storage tank is always kept full of compressed air, by a shop supply, or a special small compressor driven by the engine itself. The storage tanks must be perfectly tight, so as to preserve the pressure during a long shut-down. An extra valve is provided which will admit compressed air to one cylinder during the forward stroke, and the regular exhaust valve is set to open every stroke instead of every other stroke. When this special gear is thrown into action the engine runs on compressed air just as a steam engine runs on steam. When explosions have started in the other cylinder the special gear is thrown out of action.

A single cylinder engine is often started by running it as a compressed air engine for one or two strokes, when the fly-wheel obtains sufficient impetus to continue motion for a few strokes while regular explosions are being started. One method of doing this is to provide a special mechanically operated valve for the purpose, as in the preceding case, using compressed air from storage tanks. Another method is to provide a single quick-opening valve operated by hand. The engine is set at the point corresponding to the begining of the explosion stroke, and the valve instantly opened. The piston moves forward and when it is near the end of the stroke the valve is instantly closed. The exhaust valve opens in the regular way for the return stroke. This method only gives a single power stroke, but this is usually sufficient to enable explosions to be started. Another similar method is to supply the compressed air by a hand pump. The engine is set exactly on the back center and the clearance space filled with compressed air by the hand pump. The fly-wheel is then moved off the center by hand, and the compressed air causes a foward stroke. This system can only be used on small engines, as there is always leakage past the piston rings, so that it is impossible to pump fast enough to keep the pressure up in a large engine.

Another system of starting by compressed air in engines with electric ignition consists in adding fuel to the compressed air and exploding it by the regular igniter. This gives a much more powerful impetus than would compressed air alone. If the means for obtaining a proper mixture are known by experience and if the igniter is in good order, this is the simplest and best system.

Usually this system uses a few spoonfuls of gasoline for forming the charge. This is introduced into the compressed air pipe or cylinder. A quick opening valve is placed in the compressed air pipe, and usually there is a check valve opening towards the cylinder between the quick opening valve and the cylinder. The engine is set just at the beginning of the explosion stroke, and the electric igniter is set to spark when the piston has moved ahead a little. The compressed air valve is opened and the entrance of air vaporizes the gasoline. The pressure also starts the piston. Presently the igniter trips and and the charge is exploded. The check valve then closes automatically so that there is no escape back into the air pipe. The quick opening valve is then closed and the regular explosions started while the engine is rotating due to the impetus of the explosion. Sometimes the check valve is omitted and the quick opening valve closed by alertness after the charge is admitted and before the igniter trips. Sometimes in gas engines the charge of gasoline is not used, and instead of pure compressed air an explosive mixture of air and gas previously compressed in storage tanks is admitted to the cylinder.

In these systems of starting by exploding charged compressed air, the explosion pressure is often much higher than that occuring during normal operation owing to high compressed air pressure, coolness of the charge, and lack of dilution. There is therefore a severe strain on the engine, and wrecks have occurred in starting by this method in engines not especially designed for it.

Gas Engine Accessories.—A gas engine designer must make provision for the following accessory features, whose detailed discussion we have not space for. Cylinder cooling must be provided for; either by water used once only and wasted, by water used over and over again and cooled by radiation, or in case of small engines, by air only. Air must be led to the inlet valve from some cool place, free from dust, where the noise from the suction is not objectionable. Gas must be supplied at constant pressure and in sufficient quantity, a gas bag or other form of accumulator being used if the pipe is somewhat small and a pressure regulator if the pressure is variable. In case of liquid fuel some sort of pump, reservoir, etc., must be arranged. When electric ignition is used, a battery, dynamo, magneto or other source of current must be arranged for together with a spark coil. Some sort of muffler must be placed on the exhaust pipe. An efficient lubrication system must be provided.

Four Cycle Valve Gear Systems.—We will discuss only those valve distribution systems in general use. The exhaust valve is always mechanically operated, and we may base a classification on the system of operation and the number of the inlet valves.

The first and simplest system has a single inlet valve acting as a "poppet valve", that is automatically operated by suction and pressure. The air and fuel must be mixed in some way before reaching this valve. Throttling governing is often used with this system. Hit or miss governing is also used, generally by holding open the exhaust valve. The inlet valve does not then open as there is not sufficient drop of pressure. However, there is some slight tendency to open the inlet valve and, to avoid possibility of loss of fuel, an arrangement is sometimes provided which prevents the inlet valve from opening while the governor holds the exhaust valve open.

The second system has a single mechanically operated inlet valve. As before, the mixture is prepared at some previous point.

This is the best and most common system when throttling governing is used. However, this system is also used with hit or miss governing. In such cases, the governing is accomplished in either of two ways. The first way is to have the governor stop the motion of the whole valve driving mechanism in that position where exhaust is open and inlet closed. The second way is to have the governor connected with the inlet valve only, so that when the speed increases, it is not opened at the regular time. Normally the inlet valve is operated mechanically. By having a heavy spring on the inlet valve and a light one on the exhaust, the exhaust opens automatically and burnt products are drawn into the cylinder whenever the governor operates.

The first and second systems, using a single inlet valve, are well adopted for use with throttling governors, where the air and fuel pipes meet at the governor valve; or with hit or miss governors with liquid fuel which is vaporized as needed by the passage of the air through a mixer. With hit or miss governing and gaseous fuel the air and gas pipes simply join each other and there is a tendency for the gas to escape into the air pipe during missed cycles. Sometimes this is prevented by a check valve in the gas pipe sufficiently weighted so that the gas pressure alone will not open it, but which opens when there is suction in the air pipe. This is practically identical with a liquid fuel mixer.

The third system has a single automatic inlet with two separate sets of passages for air and fuel respectively. Hit or miss governing is always used, the exhaust being held open. Sometimes arrangements are made to positively prevent opening of the inlet valve when the exhaust is held open by the governor.

The fourth system is the same as the third except that the inlet valve is operated mechanically. The governing is effected by stopping the valve driving mechanism in the position where exhaust is open and inlet closed.

The fifth system has an automatic air inlet valve and a separate mechanically operated fuel inlet valve. In some cases the fuel valve opens directly into the air pipe and the mixed charge then passes through the automatic inlet valve. In other cases the air and fuel valves each open directly into the cylinder at separate places.

This system is usually used with hit or miss governing. The governor is arranged so as dictate as to whether or not the valve driving mechanism will open the fuel valve.

This system is also used when the governing is by throttling fuel supply only.

The time during which the fuel valve is open is then varied by the governor.

The sixth system is the same as the above, except that the air inlet valve is also mechanically operated. This is the best and commonest system for hit or miss governing or governing by throttling fuel supply only. The fuel valve is mechanically operated when the governor permits, and the air inlet valve is mechanically operated without missing.

The fuel valve may open into the air pipe or directly into the cylinder.

Mixture Regulation.—The proper kind of explosion is secured by setting once for all some kind of a regulating cock or valve in the fuel pipe. This is a "needle valve" in the case of liquid fuel.

However, if the fuel pipe be too small the air pipe must be partially closed to secure proper explosions. Sometimes a cock is placed in the air pipe for this purpose. However, such a condition should never be allowed to exist, as the power of the engine is diminished. That is to say, the air pipe must not be restricted under any circumstances.

Valve Driving.—The valves when mechanically operated, are of course driven from the crankshaft. As each operation in a four cycle engine occurs only once every other revolution, direct connection cannot be made. Various arrangements of cams and other devices have been used which perform a given function every other revolution, but these have all been abandoned for a pair of gears with a ratio of two to one. The smaller gear is on the crankshaft, and the various functions are performed by cams or eccentrics on a secondary shaft driven by the larger gear.

Cams and Rocker Arms.—In almost all cases cams act on rocker arms which move the valve stems. The cam is a separate piece keyed on the shaft and the rocker arm carries a roller to reduce the wear. Often the cam is cast iron and the roller soft steel, but a better construction is to make both of hardened steel. The rocker arm is of cast iron or cast steel. The end of the rocker arm driving the valve stem has an adjustable screw with a lock nut, which is set so that there is a very slight lost motion of the rocker arm possible when the valve is seated and the low part of the cam is toward the roller.

The cam should be shaped so as to give a rapid opening, the motion being uniformly accelerated and then uniformly retarded, then a period of rest and rapid closing.

A small auxillary relief cam is often provided opposite the exhaust cam to open the exhaust every revolution while starting.

Valves.—All gas engine valves are now of the "poppet" or "mushroom" type, as this withstands the heat the best. They are usually of cast iron, with a soft steel valve stem, driven or screwed in and riveted over. The seat is usually cut at an angle of 45° to give a wedging action and insure tightness. However, some builders use a flat seat and claim better results.

The valve stem is always led out of the side of the valve away from the combustion chamber, so that there is little or no pressure tending to cause leakage past the valve stem guide. By making long guides and keeping the valve stem a good working fit all leakage is prevented. Sometimes renewable cast iron bushings are used as guides. A collar is screwed or pinned on the lower end of the valve stem, and between it and the valve stem guide is placed a helical spring. This serves to close the valve, as the rocker arm only opens it. The spring must be heavy enough to close the valve and drive the rocker arm back as fast as the cam permits when closing.

Governors.—Gas engine governors usually consist of a pair of weights thrown out by centrifugal force against the resistance offered by gravity or a spring. The motion of the balls actuates some mechanism controlling the fuel supply.

The force balancing the centrifugal force may be simply the weight of the balls themselves, giving the ordinary Watts "conical pendulum." However, this is only adapted for slow speeds, and so an additional weight or spring is used enabling greater speeds to be maintained. The greater the speed the more sensitive the governor. Throttling governors for gas simultaneously regulate the size of orifices through which air and fuel enter the main inlet pipe. Sometimes this is done for liquid fuel also, but usually the main inlet pipe is throttled, and the fuel incidentally regulated by a mixer.

Hit or miss governors operate some mechanism which affects the valve gear so that an explosion is missed.

Gasifying Liquid Fuel.—In order that an engine shall operate successfully, the liquid fuel should be vaporized previous to ignition. A mixture of air and small drops of liquid fuel will ignite and burn, but before the combustion takes place at any point the drop of liquid fuel must first be vaporized. This makes the combustion very slow and gives a slanting ignition line. In some cases the combustion may be so slow as to last through expansion which gives a card without a peak at all, and causes considerable loss. In extreme cases there may be some unburned drops of liquid in the exhaust. This often happens in high speed engines. In order to be perfectly sure that complete vaporization has occured before ignition we should vaporize completely during admission. Some vaporization can, of course, occur during compression, but it is not advisable to count on this.

The vapor issues from the surface of a liquid until the surface is acted upon by a definite vapor pressure depending only on the temperature. In all of the cases we shall have to deal with, vaporization takes place in the presence of air, which has no effect on the vapor pressure, but reduces the rapidity of evaporation.

We can pass as much vapor as we please into the air by increasing the temperature. With any given temperature we may, of course, pass into the air any amount of vapor less than the maximum amount required for saturation. An apparatus for passing vapor of a liquid fuel into air is called a "carburetor," "vaporizer," or "mixer," according to circumstances. Ordinary usage does not definitely restrict the meaning of these terms.

Gasifying Gasoline.—Gasoline has such a high vapor pressure that a saturated mixture of vapor and air is too rich for combustion. Hence the mixture entering an engine cylinder is not nearly saturated. It is very easy to get the proper amount of vapor into the air by rapidily passing air over a small surface of gasoline, or by injecting liquid gasoline into a stream of air. That is, we simply mix liquid gasoline and air, and may appropriately call the apparatus a "mixer." Nearly all hit or miss gasoline engines use one or the other of these methods. When throttling governing is used, it is difficult to regulate the proportions of the mixture as the total amount varies, although some makers claim to do so. Most throttling, and some hit or miss engines for gasoline use some exterior apparatus which we will call a "carburetor," for making a thoroughly saturated mixture of air and vapor. This "carbureted air" is, of course, always of a uniform quality, whether the engine is loaded or not. It is used in the same way as illuminating or other gas, being mixed with a constant proportion of air at the engine. The engine itself is arranged exactly as for illuminating gas.

Carburetors.—As we shall use the term, a "carburetor" is an apparatus for forming a thoroughly or nearly saturated mixture of gascline vapor and air, so that the quality of the mixture does not change with the load on the engine. The apparatus is similar to that used for making carbureted air.

A pipe leads from the outer air through the carburetor to the gas inlet of the engine. During admission air is sucked through this pipe by the motion of the piston, and becomes fully saturated while passing through the carburetor. The original type contains passages of absorbent cloth dipping in a tank of gasoline. This system has the disadvantage that the lighter hydrocarbons of the gasoline are all evaporated before the heavier ones. Hence the quality of the gas gradually changes as the charge of gasoline is used up, and often an unusable residue is left.

Another type, open to the same objection, allows the air to bubble up from below to the surface of the gasoline.

A third type sprays a large quantity of gasoline into a stream of air. Any unevaporated portion collects in the bottom of the tank and is pumped up to be sprayed over again.

In order to supply the latent heat of vaporization the carburetor must absorb heat from without. In small engines radiation supplies enough heat. Large carburetors are buried in the ground or are surrounded by a jacket through which the hot waste water from the engine jackets is circulated. A carburetor is usually considered to be dangerous as it contains a mixture of gasoline, vapor and air. Under ordinary circumstances the mixture is much too rich to explode. However, the supply of gasoline sometimes runs low by accident, and then an explosive mixture is formed which has been known to fire back from the engine and explode the carburetor.

Gasoline Vaporizers or Mixers.—A "mixer" is an apparatus which mixes a definite proportion of liquid gasoline with air in order to form an explosive mixture ready for use in the engine. The mixture is not nearly saturated, as in the mixture formed in a carburetor. The term "vaporizer" is often used, although this is not a good name, as the vaporization takes place entirely automatically, and simply as the result of mixing. We will restrict the term "vaporizer" to cases where vaporization must be assisted by heat, as in the cases of kerosene, etc. Sometimes mixers, in very cold places, as on launches, are provided with some means of slightly warming the mixer or the air used in it, from the exhaust pipe. The mixer is always placed near the engine, however, and in most cases is kept warm enough by radiation.

The gasoline is usually injected into the air in a spray of fine drops. However, it appears probable that this is unnecessary and that the gasoline for a single explosion could be placed in the air in a single mass. The passages through the various pipes and valves would separate the mass, and each drop would instantly vaporize, as the mixture is just rich enough to explode, and therefore not nearly saturated.

There are many types of mixer for gasoline and other liquid fuels, all of which merely accomplish the purpose of introducing a more or less definite quantity of liquid into the air entering the engine. Almost any type will operate satisfactorily on hit or miss engines. In some types the amount of liquid vaporized depends on the amount of air passing. If the various parts are proportioned exactly enough, the mixture ratio will remain constant in such cases and throttling governing may be used. Often, however, the needle valve must be manipulated slightly by hand in such cases. Sometimes throttling governing is successfully accomplished with liquid fuel by use of separate air and fuel valves simultaneously regulated.

Gasifying Kerosene and Crude Petroleum. —Kerosene has a much lower vapor pressure than gasoline, and a saturated mixture at ordinary temperatures contains a large excess of air, so far as combustion is concerned. A temperature of about 150° is necessary before a fully saturated mixture will contain enough vapor to give complete combustion. Hence, in order to have no liquid present, kerosene vapor entering a cylinder must be at least at a temperature of 150° or thereabouts.

Less volatile fuels, such as petroleum, require higher initial temperatures before the vapor pressure is sufficient to form a perfect mixture with air. Of course the initial temperature must be high enough, so that if there is any cooling when the vapor strikes the cylinder walls, as often occurs, there will be no condensation. The initial heating is accomplished by some externally heated apparatus which we may call a "vaporizer."

Sometimes an oil engine is designed to use a large excess of air. Then the pressure to which the oil vapor must be brought is not nearly so great as when a perfect mixture is required, and therefore the initial temperature can be lower. The

Priestman Oil Engine is an example of this.

Other engines have the oil vapor and air in proper proportions for a nearly perfect mixture, so that the pressure of the oil vapor is about 13.7/33.11=.44 lbs. per sq. in., but the temperature is much greater than that corresponding to this pres sure. The vapor is then superheated and decomposition of the hydrocarbons takes place. This process, like that which occurs during the fractional distillation of petroleum, is termed "cracking." It is claimed that more economical results are obtained when the vapor is thus cracked. However, there does not appear to be good reason for this. If the liquid is thoroughly vaporized before ignition begins, a change in its chemical nature would make no difference. The probability is that in cases where increased economy is supposed to be obtained by cracking, that originally there was liquid present at ignition. Then gain ensues, due to further initial heating; not on account of cracking, but because the initial charge was more thoroughly vaporized.

Complete vaporization may be caused by passing the oil through chambers heated by the exhaust, but cracking requires a higher temperature and a heating flame must be employed. A heating flame is often employed, even when cracking is not attempted. An oil engine can never be started cold. In some cases where a heating lamp is employed, it is used to raise the vaporizer to a sufficient temperature before starting. In other cases an auxiliary lamp must be used, which is dispensed with when the engine is hot, or the engine is run with gasoline until it is hot enough to vaporize the oil. Cracking causes a deposit of carbon on the walls of the vaporizer, and a deposit of napthalene and similar hydrocarbons on any cool walls which the vapor reaches. Under certain conditions not very well known, this deposit may be very great. Some slight amount of cracking usually occurs even with moderate heating, and some deposits are found in all oil engines.

Oil Vaporizers.—Vaporizers for kerosene, crude petroleum, etc., usually consists of some form of mixer, such as described in the previous article, which mixes air and liquid oil spray, and some means of heating this mixture so that the liquid will be vaporized.

The remarks on types of liquid fuel mixers, at the end of the paragraph on gasoline mixers, apply to oil as well.

In hit or miss engines the most popular method seems to be to force enough oil for each charge into the air pipe by means of a pump delivering a measured quantity. A system also used to some extent has a "measuring chamber" opposite the end of the air pipe. This is a small chamber which holds exactly the quantity of oil required for a charge. This chamber is filled just before each admission stroke by an oil pump, which supplies a surplus, the excess being returned to the oil tank by an overflow pipe. When the admission valve is opened and air is sucked through the air pipe, the current draws in the oil from the measuring chamber.

A few oil engines mix only a part of the air with the oil vapor, drawing the balance of the air in separately. Still others do not mix the air and oil at all, but take them in at different points. The Hornsby-Akroyd Engine is a good example of this. There must usually be a large excess of air in such cases, as the air distant from the fuel valve is not mixed with the oil vapor at all.

There are four methods of supplying heat to vaporize the oil. The most common is to have a pipe through which the vapor passes heated by an oil torch. This also supplies heat to the hot tube igniter generally used with such systems. The second method passes the vapor through pipes heated by the exhaust. The third method has a portion of the combustion chamber unjacketed, so that it is kept red hot by the explosions. The oil is injected into the cylinder by itself and is vaporized by striking these hot walls. The hot walls also serve to fire the charge, as we shall see later. The fourth method passes the entering charge over a part of the combustion chamber, which is kept hot by insufficient jacketing, but not red hot, as in the preceding case. Unless care is taken this method will not give complete vaporization.

Igniting Devices.—The most difficult problem in gas engine design is that of ignition. In spite of the years devoted to it the problem has not yet been successfully solved, and the igniter is always a weak point in a gas engine. Formerly gas engines were unreliable on account of difficulty in starting, fuel regulation and ignition. Starting and fuel regulation are now easily accomplished, and the only remaining difficulty is ignition.

There are two general methods, electric and hot tube ignition. It is now generally conceded that electric ignition is the more satisfactory, and hot tube ignition is being gradually abandoned.

There are two general methods of electric ignition, the "contact spark" caused by breaking an electric circuit, and the "jump spark" caused by a spark discharge between two neighboring terminals with high potential difference. The contact spark is probably the most reliable when the parts do not have to move too rapidly. When the rotative speed becomes great, however, the inertia of the moving parts causes uncertain action, and the jump spark is then used, as it involves no motion.

There are two general classes of contact spark igniters, what is known as the make and break and the wipe spark.

In all cases there is a moveable "electrode," mechanically fastened to the engine in some way. One terminal of the battery is also connected to the engine at any point. The moveable electrode is therefore at the potential of this terminal. The moveable electrode is operated by mechanism of some kind connected to the valve driving gear. The other terminal of the battery is connected to a "fixed electrode" which passes through the cylinder walls, but is carefully insulated from them by mica, etc.

Make and Break Igniters.—In make and break igniters the movable electrode approaches the fixed electrode, makes contact, and suddenly recedes, the motion being perpendicular to the plane of contact, so that the electrodes do not scrape or wipe each other.

A certain amount of electrolysis always occurs, and the positive electrode is eaten away and the outer surface of the negative electrode increased. The direction of the current is frequently reversed by interchanging the lead wires, to equalize this action. The incrustation due to this electrolysis, together with a deposit of lubricating oil and carbon, frequently makes poor contacts. Often the electrodes are tipped with platinum or some alloy of platinum and iridium, with the object of making better contact. The wear of the electrodes is diminished, but there is a question as to whether the contact is improved. Another method is to allow all of the wear to come on the fixed electrode, which is arranged so as to be easily adjusted.

Wipe Spark Igniters.—In order to avoid the poor contact caused by incrustation of the electrodes, some igniters cause the movable electrode to scrape or "wipe" the fixed electrode in breaking contact. Some igniters cause the movable electrode to make complete rotations, and thus a single spark occurs. A great disadvantage of wipe igniters is the rapid wear. The electrodes must be renewed very often and must therefore be cheap and easily changed.

Jump Spark Ignition.—For very high speeds, such as with automobiles, the jump spark method is used.

A spark plug for this purpose is screwed into the engine cylinder. The two terminals are brought to a high potential difference, and a spark discharge occurs across the gap between them.

An ordinary battery supplies current to the primary of a "Rumkoff Induction Coil" with a make and break of some kind, usually operated by the magnetism of the core of the coil. The rapid rate of change of the primary current causes a high voltage secondary current and the consequent sparking. The time at which the sparks occur is regulated by a commutator upon the shaft, which makes the primary current during the proper period.

The insulation between the terminals in the cylinder must be carefully maintained so as to prevent leakage. The make and break of the primary also requires considerable attention. These two matters often give a great deal of trouble, and the jump spark is not as yet altogether satisfactory.

Hot Tube Ignition.— There are three methods of hot tube ignition, first a tube heated by an external flame and automatic timing; and second, a tube heated by an external flame with a timing valve; and third, a chamber kept hot by the explosion temperature.

Tube ignition is obtained by a thin tube open at one end to the combustion chamber and closed at the other end. An external flame, such as a Bunsen burner in gas engines and an oil or gasoline torch in other cases, brings the tube to a red heat. At admission the tube is filled with burned gases. During compression these are pushed towards the outer end of the tube by the fresh charge, the first layer of which rises higher and higher in the tube, and presently reaches the red hot part. Ignition occurs and the flame is propagated down the passage leading to the tube and into the combustion chamber. The time of ignition is adjusted by regulating the length of the tube and the point at which the flame strikes and causes the red hot zone. An accurate adjustment of ignition is, of course, impossible, although fair results are obtained. For good results a "timing valve" is used which is mechanically operated to open connection betweeu the combustion chamber and the hot tube. Electric ignition is much simpler than this and only conservative English builders use the timing valve. Many low grade American engines use untimed tube ignition on account of its cheapness. Most builders put on an electric igniter in addition to the tube however. The tubes used are often composed simply of a piece of gas pipe closed at one end and screwed into the cylinder. These must be renewed frequently, and therefore more durable tubes are often preferred, even at greater cost.

The third method of hot tube ignition is where a large unjacketed chamber is allowed to become red hot from the heat of the explosion, and serves to ignite the charge just as a hot tube does. The method is used principally with oil engines, where the hot chamber also serves to vaporize the oil, which is injected into it in a liquid state as we have previously seen.

CHAPTER XIV.

FORMULAS AND CONSTANTS FOR GAS ENGINE DESIGN.

Definite rules will be given for the size of all of the more important parts of a gas engine. The formulas are rational whenever possible, but in some cases are necessarily empirical. An attempt has been made to place everything on a more rational bases than usual. The constants and coefficients given are for the most part taken from an investigation of current practice in gas engine design made at Cornell University some years ago, and reported upon at the time.* An effort has been made to arrange everything in the most convenient form for a designers' use.

General Remarks.—The case to which the rules mainly apply is that of a single acting, trunk piston, stationary gas engine,

* Sibley Journal, June 1903.—American Machinist, 1904, Vol. 27, page 482.

between 5 and 100 horse-power. All pressures and stresses are in pounds per square inch, and all dimensions in inches. d is the cylinder diameter, and l the length of stroke, both in inches. p is the maximum pressure during normal operation. This varies from 250 to 350, the usual value being 300 lbs. per sq. inch. The stresses in the various parts which are most important are the continuously repeated stresses due to constant repetition of this normal pressure, and not the occasional higher stresses due to a high value of p produced by an excessive explosion now and then. Hence the normal value of p, rather than the occasional extreme value, is the one to be used in the formulas.

Thickness of Cylinder Walls, t.—This depends upon the stress s which can be safely allowed for continuous repetition.

Considering the cylinder as an indefinately long pipe with uniform fluid pressure, and adding a constant for reboring, crooked cores, etc., it may be shown that the thickness necessary for a stress s is

$$t \doteq (1/2s)\, p\, d + \tfrac{1}{4}.$$

Owing to the stiffening effect of the jacket, unstressed portion of walls and cylinder ends, a rather high value of the apparent stress may be used in this formula. A safe value is 2450. Then

$$t = 0.000204\,p\,d + \tfrac{1}{4}.$$

If p has the usual value, 300, this reduces to

$$t = d/16 + \tfrac{1}{4}.$$

Thickness of Jacket Wall, T, and of Water Jacket Space, j.—These are determined almost wholly by considerations of molding and casting, and depend directly on the thickness of the cylinder walls, t. Safe values are

$$T = 0.6\,t \text{ and } j = 1\tfrac{1}{4}\,t.$$

Cylinder Head Studs; Number Used, q; and Outside Dia., o.—Satisfactory results will be obtained by use of the empirical expression

$$q = \tfrac{2}{3}\,d + 2.$$

The nearest whole number must of course be used.

If the initial load on the studs caused by screwing them up is not greater than the load due to the explosion, the latter gives the maximum stress s, at the root of the threads of the studs. (The nuts may of course be carelessly screwed up tighter, causing unknown stresses). It may be shown, (since the area at the root of a thread is about 0.7 of the outside area) that the diameter necessary for a stress s is

$$o = \frac{1}{\sqrt{0.7\ s}}\ d \sqrt{\frac{p}{q}}$$

A safe value for the stress is 7800. Then

$$o = 0.0135\ d\sqrt{\frac{p}{q}}$$

If p has the usual value, 300, and q is 8 or thereabouts this reduces to $o = d/12$.

Length of Piston, L.—Let u be the ratio of the length of the connecting rod (distance between centers) to the radius of the crank. A usual value for this is about 5. Let b be the average bearing pressure on the projected area of piston (L d sq. ins.)

during the explosion stroke. The piston must be long enough to give a safe value to b in order to avoid undue wear. It can be shown that the average total load on the projected area of the piston (due to connecting rod thrust only) is $p\ d^2 \times 0.22\ \pi/4\,u$. Hence the length of piston necessary for a bearing pressure b is

$$L = \left(\frac{\pi}{4} \ \ \frac{0.22}{b}\right)\frac{p\,d}{u}$$

A safe value for b is 7 lbs. per sq. in.

Then $\qquad L = 0.025\,p\,d/u.$

If p has the usual value 300, and u the usual value, 5, this reduces to

$$L = 1\tfrac{1}{2}\,d$$

The weight of reciprocating parts gives an additional pressure on the projected area of piston, which is usually slight compared with the rod thrust. In cases where it becomes appreciable, it should be taken account of however, by adding the bearing pressure produced by weight to that produced by rod thrust, to obtain b.

Thickness of Rear Wall of Piston, z.—This depends upon the safe stress s which can be allowed. Considering the wall as a flat circular plate, fixed at the circumference, and without ribs, it may be shown that the thickness necessary for a stress s is

$$z = \left(\frac{0.41}{\sqrt{s}}\right) \quad d \sqrt{\quad p}$$

Owing to the fact that ribs are usually added to help support the wall, a high value of the apparent stress may be used in this formula. A safe value is 5320. Then

$$z = 0.00562\, d \sqrt{p}$$

If p has the usual value, 300, this reduces to

$$z = d/10$$

Length and Diameter of Wrist Pin (Piston Pin), l'' and d''.—Let s be the stress in the wrist pin due to continuous repetition of the pressure p, and b the bearing pressure on the projected area of the wrist pin ($l''\ d''$ sq. in.) at the instant of maximum pressure, when the tendency to squeeze out the oil is greatest. The length and diameter of the wrist pin must be such as to give s and b safe values. By taking the wrist pin as a beam uniformly loaded, and supported at points l'' apart, it may be shown that the diameter and length necessary for a stress s and a bearing pressure b are

$$d'' = d \sqrt[4]{\frac{\pi}{4\,s\,b}} \sqrt{p} \text{ and } l'' = d'' \sqrt{\frac{\pi\,s}{4\,b}}$$

Safe values for s and b are 10500 and 2800, respectively. Then

$$d'' = 0.0128\ d \sqrt{p} \text{ and } l'' = 1\tfrac{3}{4}\ d''$$

If p has the usual value, 300, these reduce to

$$d'' = 0.22\ d \text{ and } l'' = 1\tfrac{3}{4}\ d''$$

Area of Mid-Section of Connecting Rod, a.—Let k be the factor of safety of the connecting rod, or ratio of the breaking load to the actual maximum working load. Then the area must be such that k has a safe value. Let c be the distance from center to center of the rod, and r the radius of gyration of the mid-section. If the mid-section is round, having a diameter D, r^2 is $D^2/16$. If the mid-section is rectangular, having a height h, then r^2 is $h^2/12$.

It can be shown (by using Ritters formula for long columns; end co-efficient unity for ends free but guided; elastic limit of material, 35000; modulus of elasticity, 29,000,000; neglecting obliquity and inertia of rod, which nearly neutralize each other), that the area necessary to give a factor of safety k is

$$a = \frac{k}{44560} \; p \, d^2 \; \left(1 + \frac{0.00012 \, c^2}{r^2}\right)$$

A safe value for k is 3.9. Then

$$a = 0.0000875 \, p \, d^2 \left(1 + \frac{0.00012 \, c^2}{r^2}\right)$$

If p has the usual value, 300, and if the mid-section of the rod is circular and of dia. D and if the proportions are such that $\left(1 + \frac{0.00012 \, c^2}{r^2}\right)$ has a value of about 1.6, as is usually the case, this reduces to

$$D = 0.23\, d$$

Diameter of Crank-Pin, d'''.—This depends upon the stress, s, which can be safely allowed. Let l''' be the length of crank-pin journal, l' the length of the main bearing journal, and let m be one-half of the distance from center to center of the main bearings. A center crank engine is assumed.

$M = m - (\frac{3}{8}\, l''' + \frac{1}{4}\, l')$ is a quantity needed in our formulas. (It is the arm of the effective bending moment on the crank-pin for the stress caused by the reaction on the main bearing due to the explosion. This bending moment is the only one which need be taken into account. It can be shown that all other effects, such as inertia, centrifugal force and obliquity of rod, effect of counterbalances, weight of fly wheel, belt-pull, etc., all practically neutralize each other). Then the usual relation between stress and bending moment gives as the diameter necessary for a stress s,

$$d''' = \sqrt[3]{(4/s)\, M\, p\, d^2}$$

A safe value for s is 10,600. Then

$$d''' = \sqrt[3]{0.000379 \, M \, p \, d^2}$$

If p has the usual value, 300, and if the proportions are such that m is about $.6d$, as is usually the case, this reduces to

$$d''' = 0.41 \, d$$

Length of Crank-Pin Journal, l'''.—Let d''' be the diameter of the crank-pin, and let b be the average bearing pressure on the projected area of the crank-pin ($d''' \, l'''$ sq. in.) due to the average value of the load during a complete cycle. The length of the crank-pin must be such that b has a safe value, in order to avoid heating. It can be shown that the average value of the total load on the crank-pin, taken regardless of direction, is about $14\frac{1}{2}\%$ of the maximum load due to the explosion. Hence the length of crank-pin necessary for a bearing pressure b, is

$$l''' = \left(\frac{0.145 \ \pi}{4 \, b}\right) \ \frac{p \, d^2}{d'''}$$

A safe value for b is 213. Then

$$l''' = 0.000535 \, p \, d^2/d'''$$

If p has the average value, 300, and if d''' is $0.41d$, as shown above to be necessary in an average case, this reduces to

$$l''' = 0.95\, d'''$$

Dimensions of Crank Throws.—Let x be the thickness (in the direction of the shaft axis) of the throws of a center-crank engine, y the breadth (perpendicular to the shaft axis) and d''' the diameter of the crank-pin. Then safe values are

$$x = {}^5/_8\, d''' \text{ and } y = 2{}^1/_8\, x.$$

Diameter of Crank-Shaft at Main Bearings, d'.—This depends on the stress s at the inner edges of the main-bearing journals, which can be safely allowed. Let l' be the length of the main bearing journal. A center crank engine is assumed. $M' = 0.325\, l' + 0.090\, l$ is a quantity needed in our formulas. (It is the arm of the effective bending moment on the crank-shaft at inner edge of main bearing, for the stress caused by the reaction on the main bearing due to the explosion. It can be shown that this gives a moment equal to the combined bending and twisting moment, taking fly-wheel weight, belt pull, etc., into account.) Then the usual relation between stress and bending moment gives as the diameter necessary for a stress s,

$$d' = \sqrt[3]{(4/s)\, p\, d^2\, M'}$$

A safe value for s is 9500. Then

$$d' = \sqrt[3]{0.000422\, p\, d^2\, M'}$$

If p has the usual value, 300, and if the proportions are such that M' is about 0.4 d, as is usually the case, this reduces to

$$d' = {}^8/_8\, d$$

Length of Main Bearing Journals, l'.—A single cylinder with two main bearings is assumed. Let d' be the diameter of the crank-shaft at the main bearing, and let b be the average bearing pressure on the projected area of a main bearing ($d'\ l'$ sq. in.) due to the average value of the load during a complete cycle. The length of main bearings must be such that b has a safe value, in order to avoid heating. It can be shown that the average value of the total load on the main bearings, taken regardless of directions, and taking account of belt pull, fly-wheel weight, etc., is about $^1/_3$ of the maximum load due to the explosion. Hence the length of each main bearing necessary for a bearing pressure b, is

$$l' = \left(\frac{\pi}{24\ b}\right)\frac{p\,d^2}{d'}$$

A safe value for b is 123. Then

$$l' = 0.001068\,p\,d^2/d'$$

If p has the average value, 300, and if d' is $^3/_8\ d$, as shown above to be necessary in an average case, this reduces to

$$l' = 2\,^1/_4\ d'$$

Outside Diameter of Fly-Wheel, D.—The stress in the rim of a cast-iron fly-wheel of the usual type depends only on the velocity of the rim, v, in feet per minute. Hence the fly-wheel diameter should be such as to give v a safe value. If N is the *r. p. m.*, the diameter necessary to give a velocity v is

$$D = \left(\frac{12\ v}{\pi}\right)\ \frac{1}{N}$$

A safe value for v is 3220 ft. per min.

Then $D = 12{,}300/N$.

Weight of Fly-Wheels, W.—Let W be the total weight of all fly-wheels, in pounds, for the case of a single cylinder, hit and miss engine. Let f be the speed fluctuation coefficient. This is the ratio of the difference between the maximum and minimum number of *r. p. m.*, to the average *r. p. m.*, N. The fly-wheels must be such as to give a safe value to f. Let H be the rated brake horse power, and D the outside diameter of the wheels. The greatest fluctuation is at light loads, and the least working load is taken as when the engine misses three times between each fire. Then it can be shown (on the basis that maximum indicated horse power is the 1.4 times rated brake horse power, H; that the radius of gyration of an average fly-wheel is .83 of the outside radius; and that the ratio of the energy added to the wheel and causing the maximum acceleration in the case considered, to the net indicated energy developed per cycle if exploding every time, is 1.197) that the fly-wheel weight required to give a fluctuation coefficient f is

$$W = \frac{272\,300\,000\,000}{f} \quad \frac{H}{D^2 N^3}$$

A safe value for f for ordinary engines is 0.054 (5.4%). Then

$$W = 5\,000\,000\,000\,000 \quad \frac{H}{D^2 N^3}$$

If we have the average value of the rim velocity above found, so that D is about 12 300/N, this reduces to

$$W = 33000 \text{ H/N}.$$

THE END.

No. 47. **LINKAGES: THE DIFFERENT FORMS** and Uses of Articulated Links. By J. D. C. De Roos.

No. 48. **THEORY OF SOLID AND BRACED** Elastic Arches. By William Cain, C.E. Second edition, revised and enlarged.

No. 49. **MOTION OF A SOLID IN A FLUID.** By Thomas Craig, Ph.D.

No. 50. **DWELLING-HOUSES; THEIR SANI**tary Construction and Arrangements. By Prof. W. H. Corfield.

No. 51. **THE TELESCOPE: OPTICAL PRINCI**ples Involved in the Construction of Refracting and Reflecting Telescopes, with a new chapter on the Evolution of the Modern Telescope, and a Bibliography to date. With diagrams and folding plates. By Thomas Nolan. Third edition, revised and enlarged.

No. 52. **IMAGINARY QUANTITIES; THEIR** Geometrical Interpretation. Translated from the French of M. Argand by Prof. A. S. Hardy.

No. 53. **INDUCTION COILS; HOW MADE AND** How Used. Eleventh American edition.

No. 54. **KINEMATICS OF MACHINERY.** By Prof. Alex. B. W. Kennedy. With an Introduction by Prof. R. H. Thurston.

No. 55. **SEWER GASES; THEIR NATURE AND** Origin. By A. de Varona. Second edition, revised and enlarged.

*No. 56. **THE ACTUAL LATERAL PRESSURE** of Earthwork. By Benj. Baker, M. Inst., C.E.

No. 57. **INCANDESCENT ELECTRIC LIGHT**ing. A Practical Description of the Edison System. By L. H. Latimer. To which is added the Design and Operation of the Incandescent Stations, by C. J. Field; and the Maximum Efficiency of Incandescent Lamps, by John W. Howell.

No. 58. **VENTILATION OF COAL MINES.** By W. Fairley, M.E., and Geo. J. André.

No. 59. **RAILROAD ECONOMICS; OR, NOTES** With Comments. By S. W. Robinson, C.E.

No. 60. **STRENGTH OF WROUGHT-IRON** Bridge Members. By S. W. Robinson, C.E.

No. 61. **POTABLE WATER, AND METHODS OF** Detecting Impurities. By M. N. Baker. Second edition, revised and enlarged.

No. 62. **THEORY OF THE GAS-ENGINE.** By Dougald Clerk. Third edition. With additional matter. Edited by F. E. Idell, M.E.

No. 63. HOUSE-DRAINAGE AND SANITARY Plumbing. By W. P. Gerhard. Twelfth edition.

No. 64. ELECTROMAGNETS. By A. N. Mansfield. Second edition, revised.

No. 65. POCKET LOGARITHMS TO FOUR Places of Decimals. Including Logarithms of Numbers, etc.

No. 66. DYNAMO-ELECTRIC MACHINERY. By S. P. Thompson. With an Introduction by F. L. Pope. Third edition, revised.

No. 67. HYDRAULIC TABLES FOR THE CALculation of the Discharge through Sewers, Pipes, and Conduits. Based on "Kutter's Formula." By P. J. Flynn.

No. 68. STEAM-HEATING. By Robert Briggs. Third edition, revised, with additions by A. R. Wolff.

No. 69. CHEMICAL PROBLEMS. By Prof. J. C. Foye. Fifth edition, revised and enlarged.

No. 70. EXPLOSIVE MATERIALS. By Lieut. John P. Wisser.

No. 71. DYNAMIC ELECTRICITY. By John Hopkinson, J. N. Shoolbred, and R. E. Day.

No. 72. TOPOGRAPHICAL SURVEYING. By George J. Specht, Prof. A. S. Hardy, John B. McMaster, and H. F. Walling. Fourth edition, revised.

No. 73. SYMBOLIC ALGEBRA; OR, THE ALGEbra of Algebraic Numbers. By Prof. William Cain.

No. 74. TESTING MACHINES; THEIR HIStory, Construction and Use. By Arthur V. Abbott.

No. 75. RECENT PROGRESS IN DYNAMOelectric Machines. Being a Supplement to "Dynamo-electric Machinery. By Prof. Sylvanus P. Thompson.

No. 76. MODERN REPRODUCTIVE GRAPHIC Processes. By Lieut. James S. Pettit, U.S.A.

No. 77. STADIA SURVEYING. The Theory of Stadia Measurements. By Arthur Winslow. Ninth edition.

No. 78. THE STEAM-ENGINE INDICATOR and Its Use. By W. B. Le Van.

No. 79. THE FIGURE OF THE EARTH. By Frank C. Roberts, C.E.

No. 80. HEALTHY FOUNDATIONS FOR Houses. By Glenn Brown.

***No. 81. WATER METERS: COMPARATIVE** Tests of Accuracy, Delivery, etc. Distinctive Features of the Worthington, Kennedy, Siemens, and Hesse meters. By Ross E. Browne.

No. 82. **THE PRESERVATION OF TIMBER BY** the Use of Antiseptics. By Samuel Bagster Boulton, C.E.

No. 83. **MECHANICAL INTEGRATORS.** By Prof. Henry S. H. Shaw, C.E.

No. 84. **FLOW OF WATER IN OPEN CHAN-**nels, Pipes, Conduits, Sewers, etc. With Tables. By P. J. Flynn, C.E.

No. 85. **THE LUMINIFEROUS AETHER.** By Prof. De Volson Wood.

No. 86. **HANDBOOK OF MINERALOGY; DE-**termination, Description, and Classification of Minerals Found in the United States. By Prof. J. C. Foye. Fifth edition, revised.

No. 87. **TREATISE ON THE THEORY OF THE** Construction of Helicoidal Oblique Arches. By John L. Culley, C.E.

*No. 88. **BEAMS AND GIRDERS. Practical Formulas for their Resistance.** By P. H. Philbrick.

No. 89. **MODERN GUN COTTON: ITS MANU-**facture, Properties, and Analyses. By Lieut. John P. Wisser, U.S.A.

No. 90. **ROTARY MOTION AS APPLIED TO** the Gyroscope. By Major J. G. Barnard.

No. 91. **LEVELING: BAROMETRIC, TRIGONO-**metric, and Spirit. By Prof. I. O. Baker. Third edition.

No. 92. **PETROLEUM; ITS PRODUCTION AND** Use. By Boverton Redwood, F.I.C., F.C.S.

No. 93. **RECENT PRACTICE IN THE SANI-**tary Drainage of Buildings. With Memoranda on the Cost of Plumbing Work. Second edition, revised and enlarged. By William Paul Gerhard, C.E.

No. 94. **THE TREATMENT OF SEWAGE.** By Dr. C. Meymott Tidy.

No. 95. **PLATE-GIRDER CONSTRUCTION.** By Isami Hiroi, C.E. Fifth edition, entirely rewritten and enlarged.

No. 96. **ALTERNATE-CURRENT MACHINERY.** By Gisbet Kapp, Assoc. M. Inst., C.E.

No. 97. **THE DISPOSAL OF HOUSEHOLD** Wastes. Second edition. By W. Paul Gerhard, Sanitary Engineer.

No. 98. **PRACTICAL DYNAMO-BUILDING FOR** Amateurs. How to Wind for Any Output. By Frederick Walker. Fully illustrated. Third edition.

No. 99. **TRIPLE-EXPANSION ENGINES AND** Engine Trials. By Prof. Osborne Reynolds. Edited with notes, etc., by F. E. Idell, M.E.

No. 100. HOW TO BECOME AN ENGINEER; or, The Theoretical and Practical Training necessary in Fitting for the Duties of the Civil Engineer. By Prof. Geo. W. Plympton.

No. 101. THE SEXTANT, and Other Reflecting Mathematical Instruments. With Practical Hints for their Adjustment and Use. By F. R. Brainard, U. S. Navy. New edition. *In Press.*

No. 102. THE GALVANIC CIRCUIT INVESTI-gated Mathematically. By Dr. G. S. Ohm, Berlin, 1827. Translated by William Francis. With Preface and Notes by the Editor, Thomas D. Lockwood, M.I.E.E. Second edition.

No. 103. THE MICROSCOPICAL EXAMINATION of Potable Water. With Diagrams. By Geo. W. Rafter. Second edition.

No. 104. VAN NOSTRAND'S TABLE-BOOK FOR Civil and Mechanical Engineers. Compiled by Prof. Geo. W. Plympton.

No. 105. DETERMINANTS. An Introduction to the Study of, with Examples and Applications. By Prof. G. A. Miller. New edition. *In Press.*

No. 106. COMPRESSED AIR. Experiments upon the Transmission of Power by Compressed Air in Paris. (Popp's System.) By Prof. A. B. W. Kennedy. The Transmission and Distribution of Power from Central Stations by Compressed Air. By Prof. W. C. Unwin. Edited by F. E. Idell. Third edition.

No. 107. A GRAPHICAL METHOD FOR SWING Bridges. A Rational and Easy Graphical Analysis of the Stresses in Ordinary Swing Bridges. With an Introduction on the General Theory of Graphical Statics, with Folding Plates. Second edition. By Benjamin F. La Rue.

No. 108. SLIDE-VALVE DIAGRAMS. A French Method for Constructing Slide-valve Diagrams. By Lloyd Bankson, B.S., Assistant Naval Constructor, U. S. Navy. 8 Folding Plates.

No. 109. THE MEASUREMENT OF ELECTRIC Currents. Electrical Measuring Instruments. By James Swinburne. Meters for Electrical Energy. By C. H. Wordingham. Edited, with Preface, by T. Commerford Martin. With Folding Plate and Numerous Illustrations.

No. 110. TRANSITION CURVES. A Field-book for Engineers, Containing Rules and Tables for Laying out Transition Curves. By Walter G. Fox, C.E. Second edition.

No. 111. GAS-LIGHTING AND GAS-FITTING. Specifications and Rules for Gas-piping. Notes on the Advantages of Gas for Cooking and Heating, and Useful Hints to Gas Consumers. Third edition. By Wm. Paul Gerhard, C.E.

No. 112. A PRIMER ON THE CALCULUS. By E. Sherman Gould, M. Am. Soc. C.E. Fifth edition, revised and enlarged.

No. 113. PHYSICAL PROBLEMS and Their So-lution. By A. Bourgougnon, formerly Assistant at Bellevue Hospital. Second edition.

No. 114. USE OF THE SLIDE RULE. By F. A. Halsey, of the "American Machinist." Fourth edition, revised and enlarged.

No. 115. TRAVERSE TABLE. Showing the Dif-ference of Latitude and Departure for Distances Between 1 and 100 and for Angles to Quarter Degrees Between 1 Degree and 90 Degrees. (Reprinted from Scribner's Pocket Table Book.) Third edition.

No. 116. WORM AND SPIRAL GEARING. Re-printed from "American Machinist." By F. A. Halsey. Second revised and enlarged edition.

No. 117. PRACTICAL HYDROSTATICS, AND Hydrostatic Formulas. With Numerous Illustrative Figures and Numerical Examples. By E. Sherman Gould.

No. 118. TREATMENT OF SEPTIC SEWAGE, with Diagrams and Figures. By Geo. W. Rafter. Third edition.

No. 119. LAY-OUT OF CORLISS VALVE GEARS. With Folding Plates and Diagrams. By Sanford A. Moss, M.S., Ph.D. Reprinted from "The American Machinist," with revisions and additions. Second edition.

No. 120. ART OF GENERATING GEAR TEETH. By Howard A. Coombs. With Figures, Diagrams and Folding Plates. Reprinted from the "American Machinist."

No. 121. ELEMENTS OF GAS ENGINE DE-sign. Reprint of a Set of Notes accompanying a Course of Lectures delivered at Cornell University in 1902. By Sanford A. Moss. Illustrated.

No. 122. SHAFT GOVERNORS. By W. Trinks and C. Housum. Illustrated.

No. 123. FURNACE DRAFT; ITS PRODUCTION by Mechanical Methods. A Handy Reference Book, with figures and tables. By William Wallace Christie. Illustrated. Second edition, revised.