COMBUSTION AND SMOKELESS FURNACES

JOS. W. HAYS
COMBUSTION ENGINEER

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PREFACE

THERE has long been need of a practical and comprehensive work on Combustion as related to the efforts being made everywhere to secure smoke abatement. Much has been written upon the subject in works devoted to general engineering, and a great deal is to be found in periodical literature. These sources of information are so scattered, and each in itself so incomplete, that the average person is barred by lack of time and library facilities from making such an examination as would enable him to arrive at a clear understanding of the subject in all its bearings.

This work is designed to meet what the author believes to be the needs of those most directly interested in "Smokeless Furnaces" — the owners and engineers of steam power plants. It is too often the case that the most ignorance prevails where the broadest knowledge should be found. More examples of this fact are probably to be found among individuals directly concerned with the boiler room, than any other class. Crimes are committed against the boiler, the counterpart of which, if enacted in any other part of the plant, would call down the wrath of everybody either directly or remotely connected with the institution.

The general public are interested in the furnace and boiler. The chimney furnishes the bond of interest. One writer with a penchant for statistics estimates that a damage aggregating $40,000,000 per annum is caused by the smoking chimneys of Chicago. These astounding figures may be the result of an inflamed imagination, but the fact remains that the damage is tremendous. The movement against the smoke nuisance is attaining formidable proportions, and radical reforms in the larger centers of population cannot be much longer procrastinated.

The owner and engineer desiring to institute reforms in order to secure increased furnace efficiency, or satisfy the demands of the smoke inspector, are confronted with what is often a puzzling and annoying problem. That this problem is too often incorrectly solved, the unscientific and archaic devices installed under thousands of boilers to secure smoke abatement will bear witness.

If this volume will help to a better understanding of Combustion, and how to attain it in a scientific and practical manner in a steam boiler furnace, it will then have well served its purpose. Proper original design and installation are of extreme importance, but these matters cannot be treated in this work. To dismantle a power plant, and reconstruct it along correct lines, is only occasionally a feasible proposition. The owner is usually forced to accept the main features of a bad situation, and make only such minor and inexpensive changes and improvements as his circumstances will allow. This work is intended to help the owner and engineer to rational conclusions as to feasible devices and improvements, and to enable them to differentiate between the practical "Smokeless Furnace" and the impractical "cure-all" that had its origin in the nightmares of some crazy inventor. Nearly 1500 United States patents are to-day in force on boiler furnace devices. Hundreds of these devices are of such a nature as to amply justify the language above used.

Technical terms and formulæ will be avoided throughout the work as far as possible, — the aim being to present the subject in such form that the layman, and the man of limited experience with boiler plants, will be able to comprehend it. A list of the authorities drawn upon in the preparation of the book will be found appended.

Jos. W. Hays.

Chicago, January 10, 1906

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CHAPTER I

HEAT AND COMBUSTION

A CLEAR understanding of the laws governing combustion, and especially of such manifestations of these laws as are apparent in the furnaces of steam boilers, must be arrived at before entering upon a discussion of "Smokeless Furnaces."

"Combustion" may be defined as the chemical union of combustible matter with oxygen, "the supporter of combustion." Oxygen is a chemical element. In its free state it occurs as a gas. It is found in the air in mechanical union with nitrogen, and in water in chemical union with hydrogen. It is important to distinguish between "mechanical" and "chemical" union. Mechanical union is simply a mixture of elements. Chemical union is a combination or fusion of elements having an affinity for each other, in such manner that a substance is created possessing few or none of the peculiarities of the individual elements. It requires more or less energy to separate elements chemically combined. Little or no energy is required to separate elements mechanically combined. Hence it follows that the oxygen of the air is substantially free to combine with the carbon contained in coal, while the oxygen contained in water or carbonic acid gas is not free to enter into such combination. Apply air to the furnace fires and combustion flourishes, — apply water or carbonic acid gas and combustion ceases.

HEAT THEORIES

Heat in some degree always accompanies chemical combination, and combustion being a chemical reaction, heat is developed. What is heat? This apparently commonplace question has puzzled scientists for ages. The answer is still shrouded in more or less mystery and theory. In many of the familiar phenomena which are accepted by the common run of humanity without thought, the scientist finds his greatest problems. Why does the apple fall? The world had been satisfied with the mere fact that it did fall, until it occurred to Newton to inquire why. The theory of gravitation advanced astronomy further in one day than it had progressed in all the preceding centuries. Who shall say what potentialities are hidden in the still unsolved questions concerning heat, and its cousin, electricity? We know that when some of these questions are answered the world will get its power, its light at night and its warmth in winter direct from the energy stored in the coal. When that time arrives there will no longer be a "smoke nuisance," — furnaces and boilers will be things of the past and found only in museums where they will serve as object lessons of the world's progress.

We cannot pass without some notice of the theory of heat. Newton applied himself to the question, "What is heat?" He believed it to be some form of energy or motion; but his scientific mind was not satisfied to the point of putting forth any such definite theories as in the case of gravitation. Bacon held in a measure to the same views. They are credited by modern scientists with being nearer to the truth than the investigators who immediately followed them.

The doctrine that "Heat is a form of matter," a mysterious and subtle elastic fluid, which was termed "caloric," permeating the pores or interstices of material substances, came in time to be generally accepted. Professor Black, of the University of Glasgow, was the chief exponent of this theory, and he had a numerous following among scientists.

Rumford in 1798 and Davy in 1799, by their experiments, completely exploded the "material theory" of heat. The now universally accepted "kinetic," or "mechanical," or "dynamic" theory, as it is variously called, grew out of these experiments. This theory was further advanced by Dr. Mayer of Germany in 1842, and other contemporaneous investigators, but it remained for Dr. Joule of Manchester, in 1843, to secure its definite and general acceptance. Joule received powerful support in the celebrated Sir. William Thompson.

Rumford observed that heat was developed by the boring out of a cannon, and he reasoned that as heat was developed by friction, therefore heat must be some form or mode of motion.

Davy had arrived at the same conclusions, which were strengthened by his well-known experiments with the ice cakes. These experiments were conducted in a room which was at a temperature of 29 deg., or 3 deg. below the freezing point. Two flat cakes of ice were rubbed together with some force, and it was noticed that the ice melted at the point of contact and that the temperature of the water produced was 35 deg.

Since Joule and Thompson, it has been universally accepted that matter is composed of infinitesimal particles in a state of motion, and that friction and heat result. It was fully fifty years, however, after Davy announced his experiments and conclusions, before the scientific world was fully ready to accept the new theory. The "materialistic" school held stubbornly to its old dogmas. In explaining away Davy's experiments it was advanced that the rubbing together of the ice cakes resulted in "squeezing out" a quantity of the heat fluid or "caloric" as it was termed, and that this accounted for the increased temperature of the resulting water. The champions of the new theory replied to this argument, "If this explanation is correct, then it follows that all the heat fluid may be expelled from a substance if a sufficient amount of friction is applied. This should result in lowering the temperature of the substance to a point where it might profitably be employed as a freezing agency. Reduce some substance to this condition, and we will abandon the new theory for the old one."

Very little has been added to our knowledge concerning the nature of heat, since 1850. "Heat is a form or mode of motion." "Heat is something communicable from one body to another." We must be satisfied with these rather hazy and indefinite definitions, until the researches of some scientist shed further light upon the subject.

A great deal has been learned, however, about the properties of heat, and some notice of its various properties and peculiarities is necessary to the purposes of this work.

Distinction must be made between the terms "heat" and "temperature." In ordinary speech they are employed more or less synonymously, but incorrectly so. By "temperature" we mean the "degree of heat." "Cold" is a purely relative term. We say that a thing is "hot," when it manifests an unusual degree of heat. We say that a thing is "cold" when it manifests an unusual lack of heat. There is no point, strictly speaking, at which heat ceases and cold begins. There is such a point upon the scale of the thermometer, but it is purely arbitrary and serves the purpose of harmonizing the thermometric scale with the popular ideas of heat and cold. If we are to consider temperature from a purely scientific standpoint, the real "zero" — the point where heat actually begins — is far below the zero of the thermometer. Heat is due to the motion, and consequent friction resulting, of the particles or molecules of matter. Now there must be a point at which this motion reaches its minimum, or, perhaps, actually ceases altogether. At this point, what we call "cold" ceases, — it cannot get any colder, — and heat has its origin or beginning. This point has been definitely fixed by careful scientific calculations. It is 492.66 deg. below the freezing point of the Fahrenheit scale, and 273.7 deg. below the zero of the Centigrade. It is known as the "absolute" or true zero of heat energy.

If the molecules of matter have their minimum speed of motion, then it is reasonable to suppose that they also have their maximum speed. What is the greatest degree of heat possible? How hot is it when it cannot get any hotter? Science has figured this out to the last degree, largely by the aid of mathematics based upon the laws of gravitation. The highest temperature that man has been able to produce and record is in the neighborhood of 5000 deg. This is as nothing compared with the possibilities that are summed up in heat. If a mass of matter, a stone for instance, is dropped to the earth from a height of say 100 ft., it will have developed at the instant of impact with the earth a certain velocity due to the attraction of the earth's gravity, and the impact will result in a certain degree of heat on account of the accelerated movement of the molecules of matter due to the impact. If dropped from a greater height, the velocity of the falling stone, the impact and the heat generated thereby will all be correspondingly greater. Science has determined, to its own satisfaction at least, the limits of the earth's attraction and maximum speed with which a body falling through space from an infinite distance would approach the earth. We are told that the utmost limit of speed with which our planet could come into contact with any such celestial wayfarer, in head-on collision, is 26 miles per second, and that the impact resulting from such a collision would result in the generation of 376,916 deg. F., assuming that the total quantity of heat generated by the impact be applied to a mass of water equal in weight to the falling body. Science has amused itself with calculations to determine the heat generated by a similar collision with the sun and other bodies of larger diameter than the earth. It would be idle to follow the subject further. What has been said will serve in a way as introductory to a discussion of the "Mechanical Equivalent of Heat."

THE "MECHANICAL EQUIVALENT OF HEAT"

An understanding of the doctrine of the "mechanical equivalent of heat" is of great importance. The laws that have been formulated in connection with this doctrine underlie the science of thermodynamics and have a direct bearing upon all branches of steam engineering.

The terms, "Force" and "Energy," have been employed to a great extent as synonymous by physicists, especially in Great Britain. The tendency of late has been to limit the term, "Force," to the strict Newtonian definition, viz., "Force is any cause which alters or tends to alter a body's state of rest or of uniform motion in a straight line." "Energy," in the broad sense of the term, "is the capacity for performing work or producing a physical change." Energy may be either "actual," as for instance when a weight is falling, or it may be "potential" as when a weight is suspended. The term, "Energy of Position," is employed by some writers in preference to "Potential Energy," while other writers combine the two terms and speak of the "Potential Energy of Position." A swinging pendulum exhibits both forms of energy. When in motion it is possessed of "actual" energy. When it is stationary at the end of its "swing" and before initiating the return movement, it is possessed of "potential energy" or "energy of position." "Actual energy" is based upon and arises out of the fact of "potential energy." "Force," accordingly, is a display of "actual energy" and "force" may in turn give rise to "potential energy."

"Energy," in the broad term, is a constant quantity, — like matter, it is indestructible and cannot be created or destroyed. It neither increases nor diminishes in quantity. If it were subject to changes in quantity, the equilibrium of the universe would be disturbed and chaos would reign in place of order. While the quantity of "energy" remains the same, it may manifest itself in a multitude of forms. We have it in the form of gravitation, in the bolt of lightning, in the shock of the earthquake, and in the expansion of steam in the cylinder of the engine. Energy may change its form without abating in any degree its capacity to perform work; it may reappear at once in some other form, or it may lie dormant for ages, ready at any moment to reappear upon call in all its vigor. Take, for instance, a charge of gunpowder. Here we have tremendous energy, inactive and dormant. The gunpowder is exploded in a cannon. The energy is immediately released and almost immediately disappears. What has become of it? A portion of it reappears as sound waves, a portion gives impetus to the projectile, and other portions are to be variously accounted for. What becomes of the force imparted to the projectile? The projectile at once comes into contact with the atmosphere, and friction accounts for a portion. It comes into impact with the target and heat energy arises and gives account for a portion. Whence comes the energy in the coal? It was stored there as dormant heat energy, away back in the carboniferous period, from that great warehouse of light and heat, the sun. We burn the coal in the furnace of a steam boiler and the stored heat energy at once responds. We cause it to take the form of mechanical energy and once again it disappears.

Joule, who has already been referred to, concerned himself for years with experiments to determine the "mechanical equivalent of heat"; in other words, "what amount of 'mechanical energy' is equivalent to a given amount of 'heat energy'"; or in other words again, "if a given amount of 'mechanical energy' is caused to change its form and reappear as 'heat energy,' what amount of 'heat energy' will be produced?" Water is employed very largely in physical experiments, and Joule employed it, referring his findings to water, at a temperature of 39 deg. F., — the temperature of its greatest density. He took the amount of heat required to raise one pound of water at this temperature, one degree, as a basis for his computations. Some of his experiments were quite crude and simple. For instance, he caused a paddle to be mechanically operated in a basin of water. He measured the mechanical energy employed, and also the temperature of the water. He finally arrived, by a process of experiments too fine, and mathematical operations too abstruse to be referred to here, at the conclusion that the amount of energy displayed as heat required to raise the temperature of one pound of water one degree was exactly equivalent to the amount of energy displayed in mechanical form required to raise a mass weighing 778 lb. a distance of one foot, or what amounts to the same thing a mass weighing one pound a distance of 778 ft. These results he corrected by further experiment to 772.55. Joule gave to the world of science the British thermal unit. A British thermal unit or 1 B. T. U. is the amount of heat required to raise the temperature of one pound of water at 39 deg. F., one degree. One B. T. U. of heat transformed into "mechanical energy" will, according to the Joule determination, raise a mass weighing 772.55 lb. one foot. Later experimenters, among them Prof. Rowland, insist that the original finding of Joule, — viz., 778 foot pounds is more nearly correct, — while Reynolds and others give us figures in the neighborhood of 776. Many of the highest authorities in physics and many of the leading American schools have adopted the Rowland determination, while others adhere to the final figures given by Joule. The Joule unit is generally accepted in Great Britain, and it would accordingly seem consistent to follow the British standard or cease reckoning in "British thermal units" and adopt a unit of our own. As the Rowland experiments were conducted at Baltimore, it would be easy for those who prefer the Rowland figure to substitute "Baltimore" for "British," and thus, while not abandoning the abbreviation "B. T. U.", make plain what they mean when referring to a thermal unit. It is doubtful if an international standardizing of the thermal unit will ever be effected, for the reason that the foot pound varies with the varying force of gravitation, — the force of gravitation in any locality being determined by the density of the earth in that region. Gravity is measured by the velocity of bodies falling through space. In ordinary calculations the velocity increase per second is taken in the United States at 32.16 feet and in England at 32.2 feet.

Now that the thermal unit has been explained, it must not be lost sight of, for it is one of the inheritances of steam engineering. It enables us to determine many things, — the fuel value of coal for example. Coal has value as a fuel, primarily, only in proportion to the heat units it contains. When the coal consumer discovers that he is at the mercy of the coal dealer and awakes to a full realization of his own interests he will buy his fuel by heat units and not by pounds. The consumer is interested in the heat unit, and the price of it when he contracts for coal. Other considerations are of but secondary importance. Self-interest would seem to suggest some method of checking up on the deliveries of the coal dealer to determine whether he is unloading water, dirt, and ash in place of heat units, and whether the actual combustible itself is calorifically honest or dishonest.

The French or metric heat unit, or "calorie," is the amount of heat required to raise one kilogram of water from 4 deg. to 5 deg. C. One calorie is equivalent to 3.968 British thermal units.

The principle that "heat energy and mechanical energy are mutually convertible" has its limitations in mechanics. If it were possible to transfer one unit of heat energy, without loss, into its equivalent in mechanical energy, and then back again to one unit of heat energy, and repeat the operation, we should have a perfect engine and the problem of perpetual motion would be solved.

LATENT, SENSIBLE AND SPECIFIC HEAT

Heat possesses a number of peculiar properties. Its disposition to disappear, or become "latent," under some circumstances, is the most important of these peculiarities, both from a popular standpoint as a matter of interest and from an engineering standpoint as an element of potentiality. What is meant by "sensible" heat, should require no explanation. The thermometer registers the degree of "sensible" heat. "Latent" heat is not "sensible" to our bodies or to the fluid in the thermometer. It is not heat at all in the popular understanding of the term, but a form of molecular activity which is able to suppress from the senses all evidences of its existence. No definition can be framed that will understandingly explain "latent heat." Resort must be had to some illustrations of the way in which it acts. It manifests its peculiarities in a pronounced way in the case of water.

We will employ a piece of ice for our experiments. Now if we are able to start with the ice at the "absolute zero" of temperature, or 460.66 deg. below the zero of the Fahrenheit scale and add heat to it, the heat units absorbed will manifest their presence by a rise in the temperature of the ice. This rise in temperature will be substantially uniform, as heat is added, until we reach the melting point of ice, — 32 deg. F. or 492.66 deg. absolute. At this point a most astonishing thing happens. So long as a vestige of the ice remains, the temperature refuses to rise further. We may add heat to the melting ice in any manner we see fit, — we may pour boiling water upon it or we may heat it over a fire, but as long as any particle of the ice remains, the thermometer does not register any increase in temperature. Now in melting a pound of ice, we have added sufficient heat units to have raised the temperature, had the heat remained "sensible," 283 deg. or to 315 deg. F. All this heat is slumbering or "latent," ready to become active when occasion requires. We know that this is so, because it can be proved. The reader may have proved it himself, without knowing it. The night promises to be cold and you are afraid the plants will freeze. You place a tub of water in the room. Why? Because you have been told the water will absorb the frost and save the plants. Nothing of the kind occurs. When ice changes to water, heat is absorbed and becomes dormant. When water changes to ice, this dormant or "latent" heat awakes from its sleep and becomes active or "sensible." It warms the plants. You have seen open water "steam" on a cold day. It is giving up its "latent heat" and going back to ice. It is usually a little warmer in winter, near large bodies of water, than elsewhere in the same latitude. We say that this is due to the water. The water has nothing to do with it directly, — it is the "latent heat" contained in the water.

But let us get back to the pound of ice that we have melted to water at a temperature of 32 deg. We add more heat to the water and the temperature begins to rise again, until we reach the boiling point of water, — 212 deg. F. Add as much more heat as we please to it, we cannot raise the temperature the fraction of a degree. The water becomes steam, and the steam has a temperature of 212 deg. When the water has all changed to steam, if we add more heat the temperature of the steam will rise. Now how much heat became "latent" while we were changing this water into steam, after reaching the boiling point? 966.66 British thermal units, — enough heat, had it remained "sensible," to have raised the temperature of the water to 1178 deg. F. Over four fifths of the heat that we have added to the

AUTHOR'S NOTE: Later steam tables by Marks and Davis, now generally adopted, give the latent heat of steam a value of 970.4 B. T. U.

water since the ice was completely melted has become "latent." In this "latent heat of steam" largely resides its capacity to work for us, and drive the wheels of our mills and factories.

When the steam goes back to water, its "latent" heat is given up, just as the "latent" heat of water is released when water goes back to ice. If it were possible to convert steam to water, without losing any of this heat, the water would be red hot, and if we could convert the water to ice, without loss of heat, the ice would be white hot.

Heat, in its "latent" state, causes substances to change their form. It causes ice to change to water and water to change to steam. It causes gases to assume a more rarified state. It is thought that when heat manifests itself in this form in matter, the molecules are given a disposition to repel each other, and that, as a consequence, expansion results. Hence we have the term, "latent heat of expansion," which is that form of heat which tends to an increase of the volume of the substance to which it is applied.

The following table shows the proportions of "sensible" and "latent" heat, in British thermal units, residing in one pound of saturated steam at a temperature of 212 deg.; also the "mechanical equivalents" in foot pounds:

	B. T. U.	FOOT POUNDS
Sensible Heat	180.9	139,655
Latent Heat	966.66	745,134
Total	1,147.56	884,789

It is interesting to note just how these two forms of heat express themselves at the cylinder of the engine. The bulk of the work, to the point of "cut-off," is performed by the "latent" heat of the steam that is in the act of generation from water into steam upon the heating surfaces of the boiler. This newly generated steam forces what has preceded it into and through the mains to the cylinder of the engine and against the piston. After "cut-off," the work is performed by the "sensible" heat contained in the steam imprisoned in the cylinder and the "latent" heat, which reappears upon condensation, if condensation occurs, as "sensible." If no condensation occurs in the cylinder, it follows that the 966.66 heat units lying dormant in each pound of steam are rejected from the cylinder and lost, unless means are provided to utilize them by heating feed water, buildings, etc. It is probable that in cities where manufacturing is carried on to any extent, enough heat is wasted in this manner to keep every family comfortable throughout the entire winter.

When we speak of the "specific heat" of any substance, we mean the capacity or ability of that substance to absorb heat, as compared with water. In order to measure anything, we must have a standard, and in this case the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit is taken as such standard of measurement. We accordingly say that the "specific heat" of water at 32 deg. F. is unity, or 1, and that the "specific heat" of air, under constant pressure, is 0.2377 and of hydrogen 2.4096.

CHAPTER II

COMBUSTION AND THE BOILER FURNACE

We have now laid sufficient foundation, by our investigation of the nature and properties of heat, to enable us to proceed intelligently with a discussion of combustion. "Combustion," as we defined it in the outset, is "the chemical union of combustible matter with oxygen, 'the supporter of combustion.'" As a result of such union the molecules of matter are forced to adjust themselves in new relations, — motion and friction occur and heat is developed.

Combustion may be slow and accompanied by little heat, as when iron rusts; it may be more rapid, as when it occurs in the lungs of animals and what we call "animal heat" is developed; it may be still more violent, as when coal is burned in a furnace, or it may be instantaneous, as when powder is exploded in a gun barrel. The speed of combustion depends primarily upon the chemical affinity of the elements of the combustible, for oxygen, and secondarily upon the conditions under which the combustion takes place. Hence, when we are seeking a combustible for commercial purposes, we must select something having a ready affinity for oxygen, and we find that carbon and hydrogen meet the requirements. We have these two elements combined in coal, the carbon largely predominating. Nature has furnished us with these combustibles, and also with the supporter of combustion, but man is compelled to supply the necessary conditions to render chemical union possible at a rate sufficiently rapid to serve his purposes. Chief of these conditions of rapid combustion is temperature. "Heat aids all chemical action." When a sufficient "nest egg" of temperature is furnished, combustion is instituted and thereafter, itself, furnishes the temperature necessary to its continuance. The burning, or combustion, of any fuel, coal for instance, accordingly contemplates two operations. The first operation is a physical one, and consists of raising the temperature of the fuel by artificial means to a point where the second operation, that of chemical combination, may ensue. In other words, we must first light the fire. Our familiarity with this operation must not lead us to think that it involves matters of no more interest than matches and kindling. The commonness of any phenomenon must not be taken as evidence of its unimportance. In this instance, the question of temperatures as related to ignition is one of the most important in the whole range of our discussion of combustion as concerned with steam boiler furnaces. The various aspects of the subject will be touched upon in their proper order.

So much in a general way as to combustion; let us now note more particularly what takes place in the furnace of a steam boiler when bituminous coal is burned. We will assume the case of an ordinary return flue, multitubular boiler, mounted and set in the usual way, with an ordinary grate and fire-box, having a bridge wall at the rear. Reference may be had to the accompanying drawing, Fig. 1. We will assume the fire lighted and the boiler in ordinary service operation. We will start our observations with a "coked" fire. The volatile elements have all been distilled from the coal and the stack is clear of what is commonly called "smoke." The fuel is burning slowly, with an incandescent glow, and the boiler is receiving heat by convection from the escaping gases of combustion, and by radiation from the incandescent fuel. There is no flame at any point in contact with the boiler shell. What is the nature of the chem-

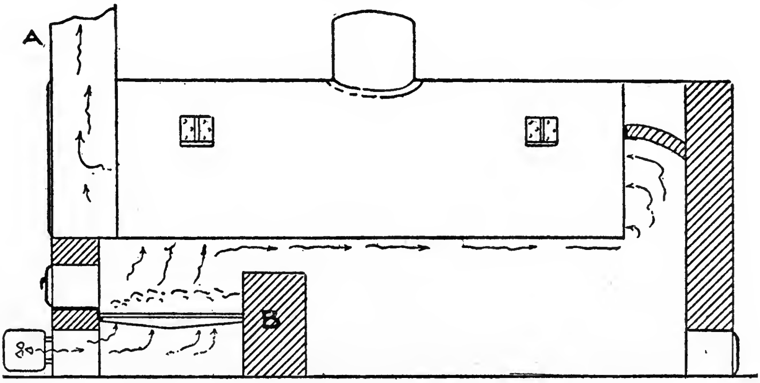


FIG. 1

ical reactions that are taking place while the fire is in this condition? Air is entering at the ash-pit doors, and is being "drawn" up through the grates and fuel by the chimney draft. We use the word "drawn" because it is implied by the term "draft." Now draft, as it occurs in a chimney, is not, strictly speaking, a pull, but may be more accurately defined as a "push." Draft is due, as everybody ought to know, to the difference in weight between the column of air that has its base at the bottom of the inside of the chimney, and a column of air of equal dimensions that has its base outside the chimney. Now the air and gases within the chimney contain a certain amount of "latent" heat, — the "latent heat of expansion" — and, owing to the fact that they are expanded, weigh less per cubic foot than the corresponding air in the other column. A struggle for equilibrium takes place, and in this struggle the lighter column is displaced or "pushed out" by the heavier one. It would avoid many misconceptions if engineering language were more accurate in its terminology.

Air is composed chiefly of nitrogen and oxygen, about 21 per cent. by volume and 23 per cent. by weight being oxygen. With the nitrogen we have no concern, for there is no practical way of eliminating it. It serves no office in combustion, and is a dead weight upon the furnace, boiler, and chimney, requiring space for its accommodation and absorbing and carrying off heat units that might otherwise be employed in the manufacture of steam. The oxygen we must have, and it is cheaper to make the best of the undesired company of nitrogen, than to attempt divorcement of the elements. Oxygen has a strong affinity for carbon, and it finds its carbon upon the grate, heated to a condition making rapid chemical union possible. The oxygen separates itself from mechanical union with the nitrogen, and unites in chemical union with the carbon in the proportion of one atom of carbon to two of oxygen. The chemical compound resulting is known as carbonic acid gas or carbon dioxide, represented by the chemical symbol (CO_2), which not only stands for the compound but the proportions of the elements entering into it. This reaction or combination occurs as soon as the oxygen and carbon get into contact with each other, in the lower strata of fuel. When one atom of carbon unites with two of oxygen, the atom of carbon is completely oxidized or satisfied with oxygen.

The oxygen, however, is not satisfied with carbon, or is not completely "carbonized," if we may use the term in this connection. The compound (CO_2) which represents complete combustion or oxidization of the combustible carbon, now takes its way, under the influence of the draft, up through the incandescent bed of fuel and emerges into the fire-box of the furnace. But it has undergone a change in transit. The carbon of the compound (CO_2) was fully satisfied with oxygen, but the oxygen was hungry for more carbon and, meeting with carbon in the passage through the upper strata of the fuel, picked up another atom of that element. The gas that emerges into the fire-box is accordingly explained by the reaction $CO_2 + C = 2(CO)$. It contains equal parts of carbon and oxygen, and is known as carbon monoxide. The oxygen of this compound is fully satisfied with carbon, or "carbonized," as we have taken the liberty of expressing it, but the carbon of the compound is not fully oxidized and is hungry for oxygen. The gas is accordingly combustible in its new state, as it is capable of further oxidization. Free oxygen is required, and if we are to burn this gas, air must in some manner be admitted into the fire-box. Carbon monoxide, as it arises from coke, is a colorless and odorless gas. It does not manifest its presence at the top of the chimney in visible smoke at this time, and we must here make the observation that a clear stack is not necessarily evidence of complete combustion. A considerable quantity of carbon monoxide, or coke gas, may be escaping unburned. A "coked" fire accordingly requires a certain amount of free oxygen in the fire-box for the accommodation of this gas, although the amount demanded is inconsiderable as compared with the requirements during the time that the coal is in process of "coking," as will be shown. Carbon monoxide burns with a purple flame, and if such a flame is present on the surface of the coked fuel, it is evidence that the gas is being consumed. If this flame is absent, the supply of air entering the fire-box should be slightly increased, either through the dampers in the fire doors or otherwise, but great care should be exercised to make certain that we are not admitting air in excess of the requirements, as in such case the surplus air will cause a loss to exceed the gain that we are making by burning the carbon monoxide.

A fact of supreme importance requires consideration at this juncture. It is fully set out in what is known as "Bertholet's Second Law." Bertholet was a celebrated French chemist who flourished in the early part of the last century, and his Second Law is as follows:

> "The heat produced in a furnace depends on the final product of combustion and not at all on whether the carbon, for example, has been, at intermediate stages, wholly or partly burned, and has existed in a greater or less proportion in the state of carbon monoxide or dioxide."

In other words, the final results are determined by the final conditions. The quantity of heat given to the boiler is determined by the final state of the gas escaping. In tracing the reactions that take place when oxygen has access to incandescent coke, we discovered that the first chemical combination occurring after the oxygen passed the grates resulted in the formation of (CO_2). The carbon entering into this compound becomes completely oxidized, and in this process yields all the heat energy it contains. If this gas could have access to the boiler shell, the maximum of the heat contained in the carbon could be employed in the manufacture of steam. But we also discovered that this gas, before it has an opportunity to reach the heating plates of the boiler, is converted to (CO), and in this conversion or "reactive reduction," heat is absorbed and disappears. Hence the heat of the gas emerging from the fuel bed and approaching the boiler shell is the heat of (CO) and not of (CO_2). Every process tending toward oxidization releases heat; every process tending away from oxidization absorbs heat. The following table will show how important it is that the gas, carbon monoxide, should be converted to carbon dioxide before reaching the shell of the boiler:

One pound of Carbon burned to Carbon Dioxide, (CO_2), yields in British Thermal Units	14,540
One pound of Carbon, burned to Carbon Monoxide, (CO), yields in British Thermal Units	4,350
Loss in Heat Units	10,190

It is of course probable that some free air would find its way through crevices in the fuel bed, and that in actual practice the loss would be much less than indicated by the table, even assuming the entire suppression of air introduction by way of the fire doors, by percolation through the walls of the boiler setting, or otherwise. The table is, however, very instructive as indicating the possibilities of loss contained in the situation.

It does not follow, however, that we can secure complete combustion of the "coke gas" we have been considering, or the "coal gas" we are about to consider, by the mere expedient of introducing oxygen. An igniting temperature must be provided, and this temperature must exist in the presence of the oxygen, otherwise we shall have no combustion. The builders of steam boilers have neglected in most cases to make the necessary provisions for the maintenance of such temperature. Their attention has been focused upon the problem of "heat absorption" to such an extent that they have overlooked many matters involved in the question of combustion. Let us see how the ordinary return tubular boiler and the common form of setting, as shown in Fig. 1, interpose agencies tending to retard combustion rather than contribute to its complete fulfilment.

At the rear of the grates is a barrier, commonly known as a "bridge wall." In addition to serving as a wall for the rear of the furnace and preventing the escape of fuel into the combustion chamber at the rear, the "bridge wall" tends to direct the currents of flame and heated gases against the boiler shell. The boiler builder aims to get these currents in contact with the heating plates as soon as possible, in order that they may be in contact as long as possible, and thus convey to the water within the boiler the maximum amount of heat permitted by the conductivity of the boiler plates. His efforts in this direction tend to check and retard the combustion of the escaping gases. The boiler shell is cold, relatively speaking. Its temperature is substantially that of the contents of the boiler. Water boils under atmospheric pressure at a temperature of 212 deg. F. Under a steam pressure of 100 lb. it boils at a temperature of 337.9 deg. It is safe to say that the shell of the average boiler will not be hotter than about 400 deg., while the temperature of the fire immediately under it may be as high as 3000 deg. The gases in such a case are subjected to the tremendous drop of 2600 deg. in extraneous temperatures, in passing from the fuel bed to the boiler shell. We can more fully appreciate these figures when we stop to consider that the drop from the boiling point to ice water is only 180 deg. Combustion depends as much upon the maintenance of the igniting temperature as it does upon the agency of oxygen. Can any one, after studying Fig. 1 in the light of these facts, express wonder that the stack of the ordinary boiler emits smoke, which is always a prima facie evidence of incomplete combustion? These chilling influences may be neutralized to some extent by lowering the grates and thereby increasing the distance between fuel bed and boiler. Combustion should be given all the opportunities possible to complete its operations before the gases are subjected to the possibilities of refrigeration contained in the cold boiler shell.

A few simple experiments will serve to verify the truth of the foregoing statements with reference to temperature and the effect of a chilling surface upon the combustion of a gaseous fuel. Place a dish, or anything presenting a cold surface, in the flame of an ordinary gas jet. Carbon is at once precipitated in a fine powder, and black smoke is formed. The extent of such precipitation registers the degree in which combustion has been checked. When the ordinary kerosene lamp is first lighted, it is likely to smoke for a few moments, if turned up to its full capacity. This is due to the fact that the chimney and the air within the chimney are cold, or at least not hot enough to insure such a state of combustion as is necessary to smokelessness. The lamp will also serve to illustrate the office of oxygen in combustion. Place a card near the top of the chimney. This will obstruct the draft passing up through the chimney, and the lamp will smoke. If the screen upon which the chimney rests, and which admits air to the flame, becomes filled with dirt, or the flow of air is interrupted in any other manner, the lamp will smoke.

Air and temperature are accordingly both necessary to the complete combustion of the gases arising from soft coal. If either is lacking, there will be smoke. The temperature of the fire-box may be raised to any degree required, but if the supply of oxygen is deficient, there will be smoke. Coal may be burned in the open air where the supply of oxygen is absolutely unlimited, and there will be smoke. The necessary temperature does not exist, — heat is dissipated as fast as generated.

We will now suppose that the furnace of the boiler under consideration, and illustrated in Fig. 1, is stoked with fresh coal. We will follow the physical and chemical operations that ensue and see what takes place.

The fuel elements contained in coal are of two classes, — fixed and volatile. The proportions that these elements bear to each other, of course, vary widely in different coals. The following table approximately expresses the composition of the several classes of coal:

	FIXED CARBON PER CENT. OF COMBUSTIBLE	VOLATILE MATTER PER CENT. OF COMBUSTIBLE
Anthracite	100 to 92	0 to 8
Semi-Anthracite	92 to 87	8 to 13
Semi-Bituminous	87 to 75	13 to 25
Bituminous	75 to 50	25 to 50
Lignite	Below 50	Over 50

We will assume that bituminous coal is being employed in the case of the boiler under consideration, and that the volatile matter is 37½ per cent. of the combustible, which would be about the average for bituminous coal, according to the above table.

As our observations have up to this time been limited to the fixed carbon or coke element of the coal, and the gases that result from its combustion, and as we are now about to observe the combustion of the volatile elements, which are so widely different in nature from the fixed carbon, we will do well to make some preliminary inquiries before commencing observation.

The gases we are now about to encounter we will term "coal gases," to distinguish them from the "coke gases" already investigated. We shall find that carbon and hydrogen enter very largely into their composition, which justifies the use of the terms "hydrocarbon" and "carburetted hydrogen." If we submit the volatile matter to the laboratory, we shall be amazed at the multiplicity and complexity of the derivable products. Some of these are as follows:

I. ILLUMINATING GASES

	SYMBOL		SYMBOL
Acetylene	(C_2H_2)	Ethylene	(C_2H_4)
Propylene	(C_3H_6)	Butylene	(C_4H_8)

II. VAPORS

Benzol	(C_6H_6)	Naphthalin	($C_{10}H_8$)

III. DILUENTS AND "IMPURITIES"

Hydrogen	(H)	Light Carburetted Hydrogen	(CH_4)
Carbon Monoxide	(CO)	Carbon Dioxide	(CO_2)
Ammonia	(NH_3)	Cyanogen	(C_2N_2)
Bisulphide of Carbon	(CS_2)	Sulphuretted Hydrogen	(H_2S)
Oxygen	(O)	Nitrogen	(N)
Water vapor	(H_2O)		

IV. COAL TAR COMPONENTS

Toluol	(C_7H_8)	Cumol	(C_9H_{12})
Anthracene	($C_{14}H_{10}$)	Pyrene	($C_{16}H_{10}$)
Crysone	($C_{18}H_{12}$)	Carbolic Acid	(C_6H_6O)
Cresylic Acid	(C_7H_8O)	Rosolic Acid	($C_{20}H_{16}O_3$)
Pyridine	(C_5H_5N)	Analine	($C_6H_5NH_2$)
Picoline	(C_6H_7N)	Lutidine	(C_7H_9N)
Collidine	($C_8H_{11}N$)	Leucoline	(C_9H_7N)

V. AMMONIACAL LIQUORS

Ammonium Carbonate	(NH_4CO_3)	Ammonium Sulphydrate	(NH_4HS)
Ammonium Sulphocyanate	(NH_4NCS)	Ammonium Cyanide	(NH_4NC)
Ammonium Chloride	(NH_4Cl)		

Here we have many of the commercial drugs, dyes, acids, and alkalis, etc., that find a sale over the counters of the drug store. It seems like sinful prodigality to consign them to the furnace of the steam boiler. The time may come, and some engineers already see it in sight, when the volatile elements of coal will be distilled on a large scale for the sake of the by-products, which will enable coke to be placed upon the market at a price sufficiently low to justify its general use in large centers where the smoke nuisance is a menace to public health.

The fireman places a quantity of green coal in the furnace upon the incandescent coke. One of the first effects to be noted, if we are equipped with sufficiently sensitive pyrometers, is a marked lowering of the temperature of the fire-box. The heat of the coked fuel is being transformed into energy, and the energy is being employed in the distillation of the volatile elements of the coal. The green coal is adding nothing to the heat of the furnace, — on the contrary it is absorbing heat and lowering the temperature. Distillation of the volatile matter must precede its combustion, and takes place at a temperature much lower than that necessary to combustion. We will note that as distillation proceeds, the lumps of coal swell and soften under the influence of the heat, and that when distillation is completed these lumps of coal are transformed into lumps of coke, much lighter than the original coal and more or less porous. We also note that the first vapors to rise from the coal are light in color. These vapors consist largely of steam. The moisture contained in the coal is being driven off. The vapors shade from light to gray, then to brown, and finally to a darker hue. The more volatile of the elements are first driven off, followed by the heavier ones. It must not be understood that each one of the volatile elements named in the above tables is isolated in the furnace of the boiler. The elements are most likely given off in mixtures, according to their natures and affinities. There will probably be light compounds of carburetted hydrogen, known as "marsh gas," heavier compounds of carburetted hydrogen, known as "olefiant" or oil-producing gas, and certain sulphur and ammonia compounds. If we should distill these gases in a laboratory at a uniform low red heat, we might isolate a large proportion of the compounds. The extent of the isolation would depend largely upon the temperature and other circumstances accompanying the distillation. If the coal, for instance, is coked in a retort at a gas works, a low temperature will be employed and the products will be few in number. The results from a ton of coal coked in this manner will be somewhere within the following figures, depending upon the nature and composition of the coal:

Pounds of coke	700 to 1,500
Cubic feet of gas	9,000 to 15,000
Pounds of coal tar	100 to 700
Pounds ammonia liquor	60 to 160

The hydrocarbons contained in coal are closely related in nature and composition to other well known hydrocarbon oils and gases, and are of great fuel value due to the presence of hydrogen. One pound of hydrogen will usually be found in bituminous coal for every seventeen pounds of carbon. As the carbon is found in two forms, fixed and volatile, and the hydrogen is found in compound with the volatile form only, it will be understood why a pound of volatile hydrocarbon fuel contains more heat units than an equal weight of fixed carbon. The following table shows the value in heat units of a pound of carbon and equal weights of hydrogen, some of the hydrocarbon compounds, and the oxides of carbon. The table also contains other interesting data of value at this stage of our investigations:

COMBUSTIBLE	B. T. U. PER POUND	POUNDS AIR REQUIRED PER POUND COMBUSTIBLE	POUNDS WATER EVAPORATED FROM AND AT 212°
Carbon	14,540	12.	14.67
Carbon Monoxide	10,100	6.	10.4
Hydrogen	62,032	36.	62.6
Olefiant Gas	21,344	15.43	22.1
Marsh Gas	26,400	16.2	26.68

It appears from the table that the heat value increases in proportion to the increase of hydrogen. We now return to our observations of the burning fuel in the boiler furnace, with an increased respect for the volatile part of it, as we have learned that, pound for pound, the hydrocarbons contain more heat units and are consequently of greater fuel and commercial value than the fixed carbon.

We note that as the temperature of the furnace rises, little tongues of flame leap along the rising gas clouds and that the flame steadily increases in volume as the temperature rises. The character of the flame also changes. In its early stages it is streaked with red and tipped with streamers of brown and black smoke. If the temperature continues to rise, and we admit a little air by way of the doors or otherwise, we will note an increase in the length of the flame, a decrease in the length of the smoke streamers, and that the flame changes from a reddish cast to a bright yellow. If we look at the stack we will observe less volume of smoke than was present when the flame presented a reddish appearance. If the temperature rises to a sufficient height, and we admit still more air, we shall find that there is another change in the character and appearance of the flame. It is now much shorter than formerly, and is white to the point of incandescence. The smoke, when we observe the stack, has greatly diminished if it has not entirely disappeared. The chances are that we shall still see more or less smoke, as the cold boiler shell, when the burning gases reach it, will check and perhaps entirely halt the processes of combustion, and unconsumed or unoxidized carbon will be precipitated and give color to the escaping gases. If we are by any means able to maintain the requisite temperature, and introduce the necessary amount of oxygen, the smoke will entirely disappear, — we shall be getting complete combustion.

Our observation of the flame in the fire-box leads us to ask several questions concerning it. What is flame? It is combustible matter in process of being oxidized. What causes it to be luminous? The luminosity is due to the heating to incandescence of the unconsumed particles of matter floating in the gas currents. The variation in the colors of the flame is due to differences in the degree of heat communicated to these floating particles of combustible matter. The higher these particles are heated, the whiter the flame. The decrease in the length and volume of the flame is due to a decrease in the number of the floating particles. The number decreases in proportion to the completeness or thoroughness of combustion. When the molecule of carbon is completely oxidized, it loses its identity in the compound into which it enters. The particles of matter take on a form of such tenuity that incandescence disappears, notwithstanding the continued presence of the heat. The appearance of the flame in the furnace accordingly enables us to determine a number of things. It tells us of the extent or degree of combustion. The whiter and shorter the flame, the better the combustion. It tells us also of the temperature of the furnace. The following table will be useful in this connection:

APPEARANCE OF FUEL OR FLAME	TEMPERATURE FAHR.
Dark Red	977°
Dull Red	1290°
Dull Cherry Red	1470°
Full Cherry Red	1650°
Clear Cherry Red	1830°
Deep Orange	2010°
White	2370°
Bright White	2550°
Dazzling White	2730°

It is not necessary to observe that a high temperature accompanies complete combustion, and that the performance of the boiler as to efficiency will have a direct relation to the temperature and consequently to the completeness of combustion.

We have much more accurate means of determining the degree of combustion than is afforded by an inspection of the flame in the furnace. We may determine the character of the escaping flue gases, and the percentage of the gases that indicate complete combustion of the carbon. We are forced in such flue gas analysis to disregard the hydrogen, as the product resulting from the combustion or oxidization of hydrogen is water, (H_2O). The coal will contain moisture to some extent and the air may be more or less moisture laden. It follows that the presence of water vapor, or steam, in the stack gases might have no connection whatever with the combustion of hydrogen or hydrocarbon volatile matter. With carbon, however, it is a different matter, as all the carbon compounds found in the stack gases must originate from the fuel. As already seen, carbon dioxide, (CO_2), results from the complete combustion of carbon, and if we know the ratio between the volume of the escaping (CO_2) and the total volume of the products carried off by the chimney, we shall have quite an accurate gage, not only of the degree of combustion but of the efficiency of the furnace as a steam producer. We have already noticed that danger arises from excess of air supply, such excess absorbing and carrying off the heat units that would otherwise be absorbed by the heating plates of the boiler. A low percentage of (CO_2) in the chimney gases may be due, chiefly, to incomplete combustion, or it may be due in a large measure to a high percentage of air. In either case such low percentage would be indicative of corresponding low efficiency, while a high percentage of the gas would be indicative of the contrary.

How much coal is wasted when the percentage of (CO_2) falls to a low level may be seen by a glance at the following table.

CO_2 AND FUEL LOSSES.

Pct. CO_2	Pct. Preventable Fuel Loss	Pct. CO_2	Pct. Preventable Fuel Loss	Pct. CO_2	Pct. Preventable Fuel Loss	Pct. CO_2	Pct. Preventable Fuel Loss
15	0.0	11.2	3.86	7.4	11.70	3.6	36.08
14.8	0.148	11.0	4.13	7.2	12.34	3.4	38.87
14.6	0.305	10.8	4.43	7.0	13.02	3.2	42.01
14.4	0.470	10.6	4.72	6.8	13.74	3.0	45.28
14.2	0.635	10.4	5.03	6.6	14.49	2.8	49.64
14.0	0.808	10.2	5.35	6.4	15.30	2.6	54.34
13.8	0.990	10.0	5.69	6.2	16.16	2.4	60.32
13.6	1.17	9.8	6.04	6.0	17.09	2.2	66.30
13.4	1.36	9.6	6.40	5.8	18.06	2.0	74.00
13.2	1.54	9.4	6.78	5.6	19.12	1.8	83.56
13.0	1.75	9.2	7.18	5.4	20.25	1.6	95.45
12.8	1.95	9.0	7.58	5.2	21.47	1.4	
12.6	2.16	8.8	8.02	5.0	22.79	1.2	
12.4	2.38	8.6	8.47	4.8	24.21	1.0	
12.2	2.60	8.4	8.95	4.6	25.76	.8	
12.0	2.84	8.2	9.44	4.4	27.44	.6	
11.8	3.08	8.0	9.66	4.2	29.29	.4	
11.6	3.33	7.8	10.51	4.0	31.28	.2	
11.4	3.59	7.6	11.09	3.8	33.58		

If combustion is incomplete, the following gases and compounds may be found among the escaping chimney gases:

Hydrogen, marsh gas, olefiant gas, benzine compounds, ammonia, water vapor, certain compounds of nitrogen and sulphur and certain hydrocarbon compounds of the type of marsh gas, etc. All are combustible except the water.

When combustion is complete, the only gases and compounds escaping from the chimney are nitrogen, carbon dioxide, (CO_2), sulphur dioxide, (SO_2), and water vapor, (H_2O). The sulphur may appear in compound with hydrogen and oxygen as sulphurous or sulphuric acid vapor. Carbon dioxide should largely predominate over all of the other gases contained in the chimney mixture, excepting the nitrogen and, as has already been said, the quantity in which it is present determines the efficiency of combustion.

The problem before the engineer who desires a smokeless chimney, and the highest possible degree of boiler efficiency, will now appear to be of simple solution and may be inferred from what has already been pointed out.

Two things are absolutely necessary for the complete combustion of bituminous coal and its gaseous elements:

1st. The introduction of air in the proper quantity, and at the right times, and in such a manner that the oxygen contained in the air will freely mingle with the gases as fast as they are distilled, and promote combustion.

2d. The maintenance of the gases at a temperature at or above their igniting points, until they are completely consumed or oxidized.

Provision must also be made for the expansion of the gases during the period of their combustion. This involves details of construction that will be touched upon at the proper time.

The problem is, however, not so simple as it appears. There are serious mechanical difficulties to be overcome, in order to introduce the air in such a manner that more benefit than harm will result. There are many things to be considered, — draft, grate area, coal used, methods of firing employed, etc., etc. The same combination of conditions probably never obtains in any two given plants. Conditions are moreover constantly changing in the same plant. Nice judgment will be required on the part of the engineer, or fireman, in charge of the boiler, reinforced, in the case of a hand-fired furnace, by certain auxiliary devices, if the highest results are to be expected.

We will first discuss air introduction. Here we find the chief difficulties and problems of the proposition. If the air question began and ended with supplying oxygen to the grates, and to the gases released above the grates, the problem would be simple of solution. The fire-doors, for instance might be left open or removed entirely, and we should have all the oxygen required for the combustion of the gases. We should, however, have little or no steam. Air regulation is necessary, and proper air regulation presents many difficulties.

A great deal depends upon the grate, but we cannot expect to get sufficient free oxygen into the fire-box by way of the grates. No grate has ever been devised that will meet the situation presented by the fire-box. If such a grate were possible, no means could be devised to regulate the amount of free air passing through it. The bed of fuel on the grates will be at times relatively thick, and at other times relatively thin. There will be clinkers at times to obstruct the flow of air, and at other times there will be air holes or fissures in the fire. The fireman can exercise some control over these matters, but his control does not go to the extent required if we are to supply air to the gases in the fire-box by way of the grates. If such supply were possible through the grates, what means could we employ to increase and diminish the supply to meet the changing circumstances in the fire-box? Air must be admitted above the fire.

Let us see if we can get at any facts that will enable us to determine what proportion of the air necessary to the combustion of our fuel must be given to the grates, and what proportion to the fire-box for admixture with the gases.

One pound of fixed carbon requires for its complete combustion 2.65 lb. of oxygen. As the proportion of oxygen and ozone in the air varies somewhat with circumstances, we will say, roughly speaking, that 12 lb. of air are required to furnish the necessary oxygen.

One pound of hydrogen requires for its complete combustion 7.97 lb. of oxygen, or in the neighborhood of 36 lb. of air.

As pointed out in a preceding table, a pound of carbon monoxide will require about 6 lb. of air, a pound of olefiant gas 15.43 lb., and a pound of marsh gas 16.2 lb.

The combined efforts of a chemist and a mathematician would seem to be necessary, if we are to determine exactly how much air to deliver to the grates and how much to the fire-box.

The authorities appear to be at great disagreement over this question. One tells us that we must introduce 10 cu. ft. of air into the fire-box for every cubic foot of gas distilled. Prof. Thurston, of Cornell University, says in his "Manual of the Steam Boiler," that from 10 to 15 per cent. of the air supply must be delivered above the grates. Another authority advises 150 cu. ft. of air above the grates for every 240 ft. through the grates. They should tell us that much depends upon the composition of the coal and other circumstances, and that no rule laid down may be considered as applicable to all cases.

Other authors instruct us as to the size of the air openings that should be provided entering the fire-box. One tells us that an air opening of from one to six square inches is necessary for each square foot of grate surface, and that the openings should be increased or diminished between these extremes according to the speed of the draft. This author says nothing about the amount of coal consumed per hour per square foot of grate, and nothing about the quality of the coal. Chas. Wye Williams, in his work on the steam boiler, recommends an opening of one square inch for each 900 lb. of coal burned per hour.

Text-books are of little value to us in our search for practical information along these lines. There are no appliances about the boiler room for weighing air and gases, and if there were, it would be difficult to employ them in such a way that they would assist us in getting the right amount of air into the fire-box at the right time. The matter of adjusting the air supply must be determined by experiment and by observation of the flame in the fire-box. Determination of the character of the flue gases — the percentage of carbon dioxide, etc. — will also be of great practical assistance. Instruments for this purpose are available and comparatively inexpensive. They should be a part of the equipment of every well conducted steam plant. Actual experiment, or, to use a homely phrase, "a process of cutting and fitting," is the only means available for determining these questions in specific cases. Theoretical generalizations and mathematical formulas are beautiful things in their way, but they are of little practical use to the engineer. Every steam boiler has its own peculiarities and must be dealt with as a separate proposition.

Much will be found to depend upon the size, shape, and location of the air passages leading into the fire-box, and the temperature of the air introduced. When we are considering the size and shape of the air passages, the element of friction must be considered, as it tends to greatly retard the speed of the air currents passing through. Frictional surface rapidly increases in proportion to area as the size of the passages is diminished. Suppose, for example, we are delivering air to the fire through one pipe, 4 in. in diameter, and we decide, in order to get better air distribution, to increase the number of pipes or inlets. What must be the diameters of the smaller pipes, and the number of them, in order that we may deliver an amount of air equivalent to that carried by the 4-in. pipe? If we make these smaller pipes 3 in. in diameter, we shall require 2.3 pipes, if 2 in. in diameter, 5.7 pipes, and if 1 in. in diameter, 32 pipes. More air will pass through a round opening than through a square or angular opening of the same area, for the reason that there is less frictional surface.

The location of the air inlets is a consideration of great importance. If the inlets are so arranged that the air when introduced into the fire-box will mingle readily with the gases, we shall be able to get combustion with a smaller surplus of air than otherwise. This stands to reason. If, for instance, air is delivered into the fire-box through the side walls, the air currents, as soon as they enter, are caught in the draft of the furnace and carried back over the bridge wall along the side walls of the boiler setting. It is manifest that if the gases in the center of the fire-box are to receive any oxygen, a large surplus of air must be introduced, if such introduction is through the side walls.

If the air is introduced above the fire, mixture with the gases will take place more readily and more intimately. The air being colder, and consequently heavier than the gases, will tend to settle, while the gases, on the other hand, will be disposed to rise. The result will be an intermingling. If, on the other hand, the air is delivered into the fire-box through openings in the bridge wall, it will enter below the gas currents, and the bulk of it will remain there until the tubes are reached. By this time the gases will probably have chilled to a point where the oxygen will be able only imperfectly to perform its office, if at all.

The temperature of the air admitted is another matter requiring consideration. It is obvious that the air and gases, upon intermingling, must strike a common level as to temperature. The colder the air, the lower will be the temperature of the mixture and the lower the net degree of heat resulting from the combustion of the gases. The air, if colder than the gases, will absorb a certain number of heat units which are thus incapacitated from performing any offices in steam generation. "Heat aids all chemical action," and the hotter the air admitted, the more intimate will be the association of the oxygen with the fuel, and the smaller will be the quantity of the air required. The smaller the air surplus, the greater will be the efficiency of the boiler.

We must not lose sight of the fact that air expands when heated, and that it is the *weight* of air employed in combustion that does the work and not the volume. Let us see to what extent air and gas expand when heated. Suppose we take air at a temperature of 62 deg. F., one pound of it will occupy 13.141 cu. ft. At 100 deg. it will occupy 14.096 cu. ft.; at 500 deg. it will occupy 24.146 cu. ft., and at 1000 deg. 36.811 cu. ft. At 3000 deg. the air will be expanded to 87.13 cu. ft. We might easily heat the air to 500 deg. before delivery to the fire-box, and in such event the air inlets would have to be of substantially double the capacity required at a temperature of 62 deg. If changes are made with a view of increasing the air supplied to the fire-box, it may be advisable to lower the bridge wall to some extent, and perhaps make other alterations, with a view of accommodating the increased volume of gases. Suppose the temperature of the fire-box is 2000 deg., and we admit more air. A pound of air at 2000 deg. will be expanded to occupy 61.94 ft. Unless extra space is provided for the accommodation of this air, between bridge wall and boiler, retardation of the draft is likely to result.

We have yet to deal with the most difficult of the problems presenting themselves, when we undertake the regulation of the air supply entering the fire-box. Before approaching this problem, we will first make some preliminary observations. The familiar "Welsbach," or mantle gas light, suggests some ideas. When the air-regulating mechanism below the mantle is properly adjusted, combustion of the gas is complete, and the flame and mantle are incandescent. If we reduce the air supply, combustion is incomplete, and we have flame and gas at the top of the mantle. If too much air is admitted, the light "dies down," the surplus air cooling the mantle to a point where a high degree of incandescence is impossible. Correct adjustment of the air supply means the brightest light and the greatest economy in the consumption of gas. What is the character of the gas we are burning in the mantle light? It is coal gas, — the same gas that we find in the furnace of the steam boiler, with some of the impurities eliminated. We would emphasize the observation that correct adjustment of the air supply is as essential to the boiler furnace as it is to the gas light. If we give the gases in the furnace too little air, we have smoke, just as in the case of the gas light. If we introduce too much air, the plates of the boiler are cooled and steam "dies down," just as the incandescence of the mantle disappears. In these respects the two cases are similar, but the difficult problem we have in mind applies to the steam boiler furnace, and not at all to the mantle gas light. In the case of the mantle light, we have a uniform pressure and supply of gas, or substantially so. Once the air supply is adjusted it requires no further attention. The situation is entirely different with the steam boiler furnace. Here the volume of gas fluctuates between wide extremes and the demand for air fluctuates accordingly. There is a large volume of gas immediately after firing the furnace with fresh coal. This volume gradually diminishes until the coal is coked, when the volume of combustible gas is comparatively very small and remains so until the next firing. Now, unless means can be devised to suit the air supply to the changing requirements, we may perhaps be better off, from a point of economy, if we make no attempts at all to add to the air supply of the fire-box. Fig. 2 will serve to graphically illustrate the contentions of the writer in this connection.

We will let the letter "D," in the diagram, indicate the point at which the furnace is fired with fresh coal, and the black triangle the volume of smoke and gas that is emitted in evidence of the incomplete combustion of the volatile matter. This volume of smoke and gas diminishes gradually from the point of maximum density, reached soon after firing, to the point "C," where the coal is completely coked and smoke entirely disappears. The stack then remains clear until the next firing, although a small quantity of invisible coke gas may be escaping. When the furnace is again stoked, the process is repeated. The space marked "t" will accordingly represent the time that elapses between the firing of the furnace and the coking of the coal, — the time during which smoke issues. "A" will represent the maximum supply of air demanded, which is the amount required to burn the maximum amount of smoke or gas emitted. The dotted line "a," "a," "a," represents the correct air supply at all the different stages between the times of firing the furnace. The maximum supply of air should be admitted as soon as the operation of stoking the furnace is completed. This supply should be gradually reduced, and reach its minimum when the coal is entirely coked. It should remain at the minimum until the next firing. The minimum supply should be such an amount as is sufficient to burn the carbon monoxide, or coke gas, given off from the incandescent fuel. Now, if we merely provide for such an air supply as would be sufficient to oxidize the maximum volume of gas; (and such provision must be made if we are to have a smokeless chimney), neglecting provision for the gradual reduction of this supply to meet the changing requirements of the fire-box, we should have the situation indicated by the dotted line, "B," "B," in the diagram. We should be filling the space "A," "C," "D," "A," with surplus air, every cubic foot of which would be robbing the boiler of heat units. We might be getting complete combustion, which in itself would mean a gain in efficiency, but we should be fortunate if the surplus air admitted would not cause a loss sufficient to more than overbalance the gain made. The boiler furnace presents all of the problems of

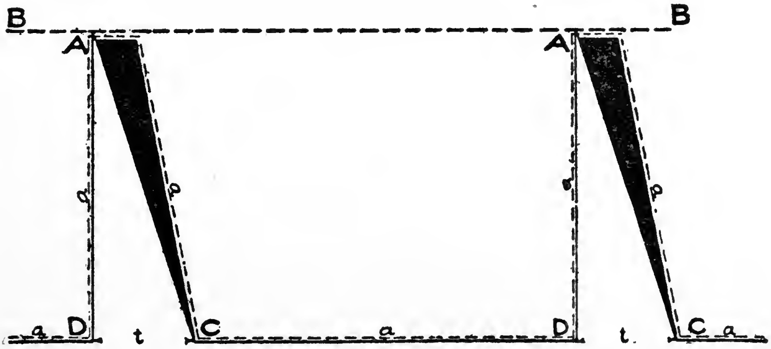


Fig. 2

the mantle gas light, with the additional problems of maximum and minimum supplies, and air reduction, added.

Common sense will support all of the above contentions in respect of air regulation. High engineering authorities may be cited if necessary.

Washington Jones, who may be considered an authority, in a contribution on Smoke Prevention, published in the *Journal of the Franklin Institute,* Vol. CXLIV, p. 38, says:

> "A furnace, immediately after a fresh supply of fuel, requires more than double the quantity of air it did the instant before, whilst we have no contrivance for furnishing such a supply, although without it throughout the space of time during which rapid gasification of the hydrogenous portion is going on, more than half the fuel consumed is wasted and passes off unburnt, becoming thereby not only totally unproductive itself, but absolutely an agent of evil, robbing the furnace of the heat absorbed in its own volatilization. All the authorities agree in this dictum, 'After a fresh supply of fuel is placed upon the grate, air must be admitted above the grate and its volume regulated by a damper.'"

In his "Manual of Steam Boilers," p. 205, Professor Thurston says:

> "Attempts to improve the efficiency of a heat-generating apparatus by 'burning the smoke' usually fail by introducing such an excess of air as to cause a loss exceeding that before experienced from the formation of smoke. Thorough intermixture of a minimum supply of air with the gases distilled from the fuel is the only means of attaining high efficiency."

Economy considered, regulation of the air supply entering the fire-box is just as important as regulation of the steam supplied to the cylinder to meet the load carried by the engine. Some ingenuity may be necessary to accomplish such regulation, but the stakes are sufficiently large to justify almost any amount of outlay and effort required.

It is directly to the point to inquire what may be the extent of the loss in case of incomplete combustion. The writer will support his views by further quotations from standard authorities.

In Thurston's "Manual of Steam Boilers," p. 189, will be found a report of an exhaustive and scientific test, made for the purpose of determining the amount of waste resulting from the incomplete combustion of the gaseous elements of bituminous coal. A steam boiler equipped for service operation was employed in the tests. In summing up his comments upon these tests, Professor Thurston says:

> "The transformation of a mass of black smoke into a flame many feet in length is the best possible evidence of the advantage of this operation. The gain in economy of fuel was estimated at about one third when the supply of air was properly adjusted and managed."

On page 186 of the same work Professor Thurston says:

> "The highest efficiency of heat production is secured by perfect combustion with the least practicable air supply, obtaining the highest possible resulting temperature."

And again on page 205 we find Thurston expresses himself:

> "With too thin a fire the danger arises of excess of air supply; with too thick a fire, carbon monoxide may be produced. In the former case, combustion will be complete, but the heat generated will be distributed throughout the diluting excess of air, and thus rendered less available and the efficiency of the furnace correspondingly reduced, while in the latter case a loss arises from incomplete combustion, and waste takes place by the passage of combustible gas up the chimney."

Professor Rankine, of the University of Glasgow, is an authority of such weight that he is frequently quoted in the works of Professor Thurston. In his "Manual of the Steam Engine," p. 291, Professor Rankine says:

> "The greatest probable amount of waste, when the absence of any provision for introducing air to burn the inflammable gases is combined with bad firing, may be estimated by taking the proportion in which the total heat of the combustion of the coke or fixed carbon contained in one pound of coal is less than the total heat of combustion of all the constituents of one pound of coal."

This would seem to mean that conditions are possibly so bad as to result in a total loss of all of the volatile fuel contained in the coal. Now let us see what Professor Rankine would estimate as the probable percentage of loss under such circumstances.

Taking reliable analyses of the coals produced by ten random Illinois counties, and computing the averages, we find the heat value to be 10,670 British thermal units per pound of coal. We also find that these coals contain an average of 48.484 per cent. fixed carbon. One pound of carbon, as has been seen, contains 14,540 British thermal units; 48.484 per cent. of 14,540 gives us 7049 British thermal units residing in the fixed carbon. Invoking Professor Rankine and subtracting 7049 ("the total heat of combustion of the coke or fixed carbon contained in one pound of coal") from 10,670 ("the total heat of combustion of all the constituents of one pound of coal"), we get a balance of 3621 British thermal units. This is 33.926 per cent. of the energy, or fuel value of the coal, and Professor Rankine says that it is possible to operate a plant along such unscientific lines that this amount — the entire volatile element of the fuel — will pass up the chimney and be lost.

Hollis W. Field is responsible for the following statements:

> "When soft coal of any class is burned in a way to spread a cloud of smoke around the top of the stack, to the point of making a nuisance of the plant, nearly three times more energy is going out of the flue than is given to the main belt at the fly-wheel, and when the stack is smoking, as so many stacks do smoke, it may be figured that a good dividend on a large block of stock in the concern is going out into the upper air every thirty days.
>
> "But considering that the coal has been shoveled in to the best advantage known to modern practice, there will be a small cloud only, at the top of the stack, and yet in this vaporous discharge of smoke, not nearly approaching the need of a smoke inspector, 2970 units of the 14,540 will be discharged as a waste that is impossible of recovery in any form. This is almost one fifth of the possibilities of the coal under the best that can be done; when a stack is hooded for half its length in a dense nimbus of coal smoke, perhaps half of the value of the coal in the firebox has escaped in carbon and in gases."

Some interesting conclusions can be deduced from the following figures, which are taken from good engineering authorities:

The efficiency of a furnace and boiler is reckoned from the proportion that the heat absorbed by the boiler bears to the total heat units contained in the coal. It requires a good boiler of the multitubular type, and fair conditions of operation, to show an efficiency of 60 per cent. This leaves 40 per cent. of waste to be accounted for. The escaping stack gases will probably have a temperature of 600 deg., and this waste of heat units released in the furnace will approximate about 22 per cent. A portion of this loss is preventable and may be charged to the heating of unnecessary excess air. Probably 2 per cent. of the fuel will be lost through the grates and 4 or 5 per cent. of the heat will be lost by radiation. This leaves a balance of around 12 per cent. that we are at a loss to account for in figuring up a "heat balance." Many engineers charge the "unaccounted for" loss to Methane and other hydro-carbon gases. Much remains to be learned about what really takes place in a furnace burning a complex hydro-carbon fuel.

The following conclusions must be drawn:

First, that "smoke means waste;" second, that under right conditions smoke may be consumed or "prevented;" third, that smoke may be burned or prevented without securing an increase in efficiency—that smokeless combustion does not necessarily mean economical combustion; fourth, that complete combustion, coupled with proper air regulation, means a large saving of fuel and that if combustion is improved without such saving the fault may be charged to improper regulation of the air entering the firebox.

The direct fuel wastes attributable to "smoke" have been greatly overestimated by many writers. There may be a great deal of "smoke" and very little of fuel value going up the chimney, or there may be very little smoke and a great deal of waste combustible in the chimney gases.

Low boiler settings explain more smoke than any other one cause, and where smoke is caused by the snuffing out of the flame upon a cold surface, as in the case of a low set boiler, there may be no trace of combustible gas in the floating soot. The fuel lost in the soot itself is almost negligible. The fuel lost through the insulating effect of soot on the heating surfaces is not negligible by any means. It is a serious loss. Soot ranks away ahead of asbestos as an insulating material. The slightest coating of it upon the tubes or heating surfaces of a boiler will cause a marked difference in the coal consumption. The loss is not so much in the soot that goes up the chimney. It is in the soot that sticks to the boiler and does not go up the chimney.

Author's Note:—For a further discussion of Soot, see Appendix.

CHAPTER III

COMBUSTION AND THE STEAM BOILER

The steam boiler in its relation to the boiler furnace, and the combustion of fuel therein, must have some attention before we pass on to a direct discussion of the smoke evil and the devices that are being offered to accomplish its suppression.

The boiler usually interposes some obstacles in the way of attaining complete combustion. These obstacles vary in their nature with different types of boilers. We must understand wherein the difficulties lie; we must also know the peculiarities of the various styles of boilers in common use, so far at least as such peculiarities have a bearing on the subject of combustion.

What are the requirements of a good boiler? Let us consult an authority. Professor Thurston, who has already been quoted, gives us a list of the requirements in the order of what he considers their relative importance. They are as follows:

A good boiler must be adapted and the builder should be required,

"1st. To secure complete combuston of the fuel, without permitting dilution of the products of combustion by excess of air."

"2d. To secure as high temperature of the furnace as possible."

"3d. To so arrange heating surfaces that, without checking draft, the available heat shall be most completely taken up and utilized."

"4th. To make the form of boiler such that it shall be constructed without mechanical difficulty or excessive expense."

"5th. To give it such form that it shall be durable under the action of the hot gases and of the corroding elements of the atmosphere."

"6th. To make every part accessible for cleaning and repairs."

"7th. To make every part, as nearly as possible, uniform in strength and in liability to loss in strength by wear and tear, so that the boiler when old shall not be rendered useless by local defects."

"8th. To adopt a reasonably high factor of safety in proportioning."

"9th. To provide efficient safety valves, steam gages, and other appurtenances."

"10th. To secure intelligent and very capable management."

The first two requisites, only, come within the purview of our discussion. That they are placed at the head of the list would seem to indicate their supreme importance.

We will quote further from Professor Thurston, as we know of no higher authority:

"In securing complete combustion an ample supply of air and its thorough intermixture with the combustible elements of the fuel are essential; for high temperature of furnace it is necessary that the air supply shall not be in excess of that actually needed to give complete combustion. The efficiency of a furnace burning fuel completely is measured by the formula

$$E = \frac{T - T'}{T - t}$$

in which E represents the ratio of heat utilized to the whole calorific value of the fuel; T is the furnace temperature; T' the temperature of the chimney, and t that of the external air. Hence, the higher the furnace temperature, and the lower that of the chimney, the greater the proportion of available heat."

Boiler builders as a rule have given attention to the third requisite at the expense of the first two. How this has come about will be better understood if we follow briefly the evolution of the steam boiler from its primitive forms to the modern types.

James Watt was among the first to make use of a steam boiler for power purposes. The style first adopted by Watt came to be known as the "wagon" boiler, owing to its general resemblance in shape to a wagon with a canvas cover. The boiler was provided with a passage for flame and gases, beneath the plates, throughout its entire length, and with passages for similar purposes at the sides. The "wagon" boiler gave place to the plain cylindrical form.

The desirability of more heat absorbing surface soon became apparent to the early boiler builders, and what is known as the

"Cornish" boiler was the first result of the efforts in this direction. This type is provided with a large return flue, running throughout the length of the boiler. This was soon improved upon by twin flues, in the type known as the "Lancashire" boiler. The result of these modifications was such an increase in efficiency, that the flues idea was shortly carried to the extreme of development. The return tubular boiler, as we have it to-day, is a direct descendant of the early "Cornish" boiler.

It was soon conceived that a furnace placed within the boiler would expose more heating surface than if located beneath the boiler shell. The internally fired boiler is an outgrowth of this conception. The furnace and ash-pit are placed within a large flue, which is completely surrounded by water. A conspicuous example of this type is the "marine" boiler, largely employed upon steam vessels owing to the relatively small space occupied and the absence of any necessity for a setting of masonry. The steamer is usually followed by a dense cloud of smoke, which is directly chargeable to the influence of the cold surfaces of the "marine" boiler upon the burning gases. Such a desideratum as complete combustion is out of the question where one of the main requirements of combustion is sacrificed to heating surface.

The first water-tube boiler made its appearance in 1793. This type, in late years, appears to be increasing in popularity. Among the other advantages claimed, is large heating surface and provision for the rapid circulation of water.

Having shown that the first and second requisites have been sacrificed, in the evolution of the steam boiler, for the benefit of the third, we will look a little more closely at the modern types. Steam boilers are usually classified as "stationary," "locomotive," and "marine." For our purposes we will adopt two general classifications, "externally fired" and "internally fired." Locomotive and marine boilers will of course be included in the second classification. Most water-tube boilers will class as externally fired. We must, however, adopt a sub-classification for the water-tube type, as those conducting the gases directly to the tubes present problems as to combustion not offered by those first conducting the gases into a combustion chamber after the manner of the return-tubular boiler.

As we have already dealt to some extent with the externally fired return-tubular boiler, little further need be said at this juncture concerning it. The result of bringing the burning gases too soon into contact with the cold boiler shell was pointed out in connection with the illustration, Fig. 1.

The type of water-tube boiler that conducts the gases at once among the tubes offers great obstacles to the completion of combustion and is usually a bad "smoker." We have already shown that the burning gases must have opportunity for expansion while in a state of combustion. Such opportunity is almost entirely lacking in the type now being considered. The bridge wall rises into contact with the water tubes, and the tile baffle plates between the tubes are arranged in vertical formations. The burning gases rise vertically from the fire-box, and are at once in contact with the cold surfaces of the water tubes. The elements of time and space, necessary to the completion of combustion, are both lacking. There may be good grounds for the arguments usually advanced in favor of such a boiler, — viz., that it offers superior circulation of water through the tubes, owing to the application of the greater degree of heat near the point where the tubes enter the water legs; that the gases are brought earlier into contact with the tubes, and a greater degree of heat extracted than would otherwise be possible, etc. We have no concern with these arguments, as our province is limited to combustion. Having combustion and smoke elimination in mind, the only hope of satisfactory results where such a boiler is employed lies in what is commonly termed a "Dutch oven" furnace, exterior to the boiler proper and its setting, and the use of the space occupied by the furnace and ash-pit of the boiler,

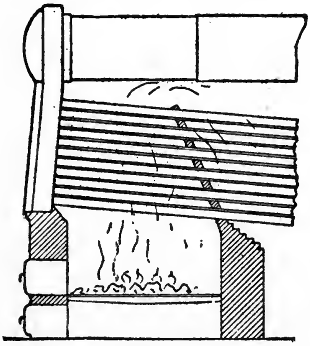


FIG. 3

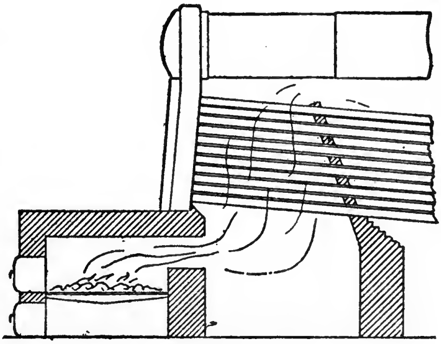


FIG. 4

as a combustion chamber. This type of boiler is partially illustrated in Fig. 3, and the application of the "Dutch oven" suggested in Fig. 4. There are a number of objections to the use of a "Dutch oven," to which we will call attention later.

With the water-tube boiler employing a combustion chamber at the rear of the bridge wall, the same arguments apply as in the case of the return-tubular boiler. In this type the baffle plates are disposed between the tiers of tubes and parallel with them, the gases being first conducted through the combustion chamber and then up, for circulation among the tubes. If what is known as "enveloping tile" are employed upon the lower tier of tubes, considerable assistance will be rendered to combustion, chilling contact of the gases with the cold tubes being thereby avoided.

"Dutch oven" furnaces can also be employed, with good results as to combustion, in the case of all internally-fired boilers. Such expedient is, in fact, about the only resource in such cases, if anything approaching complete combustion is desired.

There is a growing tendency to give combustion more of a chance by giving the furnace more space. The most active of all the causes of smoke is lack of space. The old theory seemed to be that there should be just room enough between the boiler and the grates to permit building a fire. We are getting away from that idea. What is known as the "Hartford specification" for the setting of return tubular boilers called for a distance of 28 inches between the grates and the shell of the boiler. That specification is still being followed, bad as it is. In fact, it is quite unusual to find a boiler of the return tubular type set in any other manner. Any boiler so set with an ordinary furnace will cause smoke and a lot of it.

A prominent boiler insurance company has just issued a specification for the setting of return tubular boilers. It calls for a distance of 48 inches between the boiler shell and the grates. This is none too much. In a New York power station the tubes of the water tube boilers are 15 feet from the grates.

The man with the smokeless furnace to sell will find a poor field for his activities when we learn how to build furnaces and set boilers that are suited to the burning of bituminous coal.

CHAPTER IV

"THE CHIMNEY EVIL"

The smoke evil is the greatest "nuisance" in the world. This is a broad statement, but the figures are available to prove it. Other nuisances may be more intensely charged with evil, but they are usually confined to narrow localities and affect comparatively few people. The smoke evil, by reason of its widespread prevalence, the millions that come under its influence and the hygienic as well as economical considerations involved, easily ranks as the chief of all nuisances. The "chimney evil," would be a more all-embracing term for the nuisance, for the chimney is responsible for more things of an evil character than are embraced in the word "smoke," as it is commonly employed and understood. When the "chimney evil" is better understood, there will be a general amendment of smoke ordinances. The smoke inspector will then be required to determine the nature of the poisons the chimney is contributing to the atmosphere. He will devote to flue-gas analysis the time that he now spends at his roost upon the top of some high building, making notes of the colors that display themselves about the tops of neighboring chimneys. When the flue gases are right, in their nature and proportions, there will be no smoke to offend the esthetic tastes of anybody. Such smoke as is obnoxious to the ordinances may be absent, and yet there may exist such an output of poisonous gases as to impair the health of everybody. What are the real evils in connection with the smoking chimney? There is so much misapprehension upon this subject, that a careful inquiry into the various aspects of the nuisance is apropos and timely.

The "chimney evil" must be considered from two standpoints: first, a hygienic point of view, the public health taken into account; second, an economical point of view, damage to and waste of property being in mind. Our inquiries from the second standpoint should follow two distinct avenues, (*a*) damage to public and private property, and (*b*) wastes in the plant with which the chimney is connected, due to incomplete combustion.

As health is a matter of greater moment than mere dollars, the hygienic point of view is the one more directly concerning the public. The chimney evil is a menace to health, but the greatest dangers lie, not so much in the black and unsightly element commonly called smoke as in the noxious gases and vapors that accompany black smoke and are sometimes emitted from the stack in the entire absence of visible smoke. These gases and vapors have already had some attention, but we will look into them a little further.

Over one third of the fuel elements of soft coal, on the average, consist of volatile matter, and may, if conditions are extremely bad, be given off through the stack. From 500 to 700 lb. of the constituents of one ton of coal may, accordingly, in aggravated cases, be discharged into the atmosphere. To this must be added such combustible carbon monoxide gas as is given off from the coke after the volatile element is distilled. These figures are of course far above the average; they are cited only as indicative of the extent of evil of which the chimney is capable. What proportion of this tremendous possible output concerns the anti-smoke ordinance? In other words, what proportion of the discharge from the chimney is in visible form as floating carbon, and offensive from the standpoint of the smoke inspector? Under no possible circumstances more than 2 per cent. of the chimney discharge, or 1 per cent. of the weight of the coal. The average will be far less than these figures. A very small amount of soot, by weight, is sufficient to give color to a very large volume of gas. What shall be said of the other 98 per cent. of the chimney output? Has the public no concern with it because it is invisible? No such argument would be raised in favor of immunity for the small-pox microbe.

Is there anything inimical to health in soot? It may tend to clog our nostrils, and to some extent to block the air passages of the lungs. It may tend to shut out the sun, and rob us of sunlight, which is more or less necessary to health. This is about the extent of the evil that the smoke inspector is fighting, so far as public health is concerned. Carbon is inert, non-poisonous, and is not destructive of the tissues. Coal mining, barring the physical dangers attending it, is a healthful occupation and the coal miner is usually long-lived. Postmortem examinations have developed the fact that the lungs of the coal miner may be absolutely black with the coal dust inhaled for years, and these organs be otherwise in a sound and normal condition.

Whatever may be said of the free carbon floating in the gases, the gases themselves are not entitled to any claims of innocence. Let us see how powerful the gas, carbon monoxide, is as a health and life destroying agent. This gas is one of the chief constituents of "water gas," the commercial gas supplied in most cases for lighting and cooking purposes, and we know the result of inhaling fuel gas to any extent. An atmosphere impregnated with carbon monoxide to the extent of one one-hundredth of one per cent., if breathed for a sufficient length of time will cause death. If the air is impregnated to the extent of 5 per cent., the result is speedy asphyxiation. It is claimed by high medical and chemical authorities that the deadly effects of carbon monoxide are greatly increased when this gas is mixed with carbon dioxide, or carbonic acid gas. One half of one per cent. carbon monoxide, in company with 5 per cent. carbonic acid, when inhaled, is as quickly destructive of life as 5 per cent. of carbon monoxide. When inhaled, carbon monoxide causes certain active chemical changes in the blood, directly affecting the heart and brain. The fact that this gas is colorless and odorless, and we are therefore unable to detect its presence, renders it all the more insidious. It is fortunate for the dwellers in large cities that carbon monoxide is of less specific gravity than air; notwithstanding its lighter gravity, we get more of it than is good for us, the amount we are forced to breathe depending somewhat upon atmospheric conditions. If smoke fresh from the stack is inhaled, the lungs are compelled to entertain this poisonous element in some quantity. No chimney should be tolerated, the fresh smoke from which is able, under any circumstances, to enter the windows of any occupied building. The mere fact that the result of breathing smoke-laden air is not immediately fatal is no argument for the toleration of the evil. The cumulative effects of poison taken for a long time in small quantities may be entirely disastrous in the end.

We have already noticed that the absence of black smoke cannot be taken as proof of the absence of poisonous combustible gases. This is a fact of such supreme importance in connection with the chimney question that it will bear repetition. Let us see under what circumstances combustion may be incomplete in the absence of offensive smoke.

A change in method of firing might result in an apparent change in volume of smoke emitted, while the actual volume might not be in the least diminished. Suppose, for instance, a furnace is fired every 20 minutes, and eight scoops of coal, four to each fire-door, placed in the furnace at each firing. If conditions as to temperature and air above the fire should be bad, a dense volume of black smoke would result after each such firing, which might continue for six or seven minutes, gradually diminishing in intensity until the stack would clear of visible smoke, at which condition it would remain until the next firing. The smoke inspector is shocked and registers his protest. The engineer then changes the method of firing, and two scoops of coal, one to each fire-door, are placed in the furnace at intervals of five minutes. It is evident that the smoke resulting from two scoops of coal will be less in volume and density than that from four times the quantity. If conditions are such that better combustion should not result from lighter firing, it must follow that the chimney would be putting forth every 20 minutes the same volume, both of gas and free carbon (though the quantity at any given moment might not be sufficient to constitute a violation of the smoke ordinance), that was emitted during 20 minutes when all of the eight scoops of coal were placed in the furnace at one stoking. It makes little difference, so far as the actual nuisance is concerned, whether the discharge of a given volume of smoke is limited to the fraction of a given period of time, or whether it is distributed in a continuous, but less pronounced manner, over the entire period. It is probable that the lighter firing would to some extent improve combustion, but not necessarily so. Other methods of firing may be employed to fool the public and the smoke inspector, without necessarily diminishing the smoke nuisance in the least particular.

"Smokeless furnaces" are not always what they seem. It is possible to remove the free carbon or soot from the gases, and show a clean stack, without in the least improving combustion, — in fact, it is even possible to show a clean chimney by the employment of means which have a reactive effect upon combustion, and result in greatly increasing the output of poisonous gases. This statement appears absurd upon the face of it, but it is one of the many well proved, if strange, facts developed by a close study of combustion. The author may perhaps do well to marshal some authorities in support of this contention.

L. W. Dimond, in his admirable work upon the Chemistry of Combustion, refers to this matter. He speaks of certain classes of "smokeless furnaces," which employ the expedient of passing the gases over highly heated surfaces of metal or tile, and makes the following observations:

> "When from an insufficient or redundant supply of air, or from other causes, combustion is incomplete, the carbonaceous constituent of the coal is set free in the form of smoke. This smoke is made to pass over heated bars of iron, or other heated substances, and, as we are gravely told, is 'consumed.' Carbonic acid is always mingled with the smoke, and when the two are brought together at a high temperature, as by contact with the heated substances, the invisible carbonic acid and the visible smoke unite (in the manner before described) and produce invisible carbonic oxide. This we are asked to believe is 'burning smoke'; but in truth, the form only is changed without saving the least fraction of heat."

This author might also have added with perfect truth that there is an actual loss of heat when such operation occurs. Berthollet's Second Law, which we have already noted, applies in such a case. We have shown how carbonic acid gas may be reconverted by a reactive operation to carbon monoxide, when free carbon is encountered in the absence of sufficient oxygen. Such free carbon is present in smoke, — it is what gives smoke its color. It is accordingly true, as pointed out by Dimond, that when carbonic acid gas and smoke encounter each other in the presence of temperature and the absence of oxygen, there is a union resulting in carbon monoxide, and a disappearance of visible smoke. Such reactive operation is attended by the absorption or disappearance of heat.

It is necessary at this stage of our argument to advert to "steam jets" to some extent, while leaving a more extended discussion of these devices until later.

A "steam jet," properly installed and operated, will usually diminish, if not entirely suppress, black smoke and satisfy the smoke inspector; but what are the results where a "steam jet" is employed, with respect to combustion and the character of the chimney gases? Eckley B. Coxe, in the Transactions of the New England Cotton Manufacturers Association, session of 1895, tells of tests made to determine the relative efficiency of mechanical draft with fan blower and a "steam jet smoke consumer" device. The appearance of the smoke issuing from the chimney was not relied upon as necessarily indicative of the state of combustion. Flue gas analysis was employed and the results were extremely illuminating as to the "steam jet." The following table shows the results of the analysis:

	PER CENT. OXYGEN	PER CENT. CARBON MONOXIDE	PER CENT. CARBON DIOXIDE	PER CENT. HYDROGEN	PER CENT. MARSH GAS
Fan Blower.	1.20	0.40	16.80		
Steam Jet...	0.30	13.15	8.20	11.08	2.00

Note the tremendous increase of carbon monoxide, the poisonous product of incomplete combustion; the decrease of carbon dioxide, the product and evidence of complete combustion; and the presence of the highly combustible marsh gas, — all resulting from the employment of the "steam jet." There was also a large percentage of hydrogen, resulting from the dissociation of the hydrogen and oxygen contained in the steam. The presence of this hydrogen among the gases is indicative of a great waste of heat, as the dissociation of the hydrogen and oxygen contained in one pound of steam represents the conversion and disappearance of substantially 62,000 British thermal units, equal to the energy contained in about four and one half pounds of pure carbon. Is it possible to present stronger arguments in favor of the abandonment of stack observations by the smoke inspector and the adoption of flue gas analysis instead? The smoke inspector of course has no concern with furnace or boiler efficiency, but he should be directly concerned with the character of the gases the chimney discharges into the atmosphere to be breathed by the tax payer. The public and coal consumer should be upon their guard against all devices which apparently improve combustion, but as a matter of actuality retard it and multiply the output of poisonous elements.

Other poisonous elements are discharged by the chimney, but they do not possess anything approaching the virulent properties of carbon monoxide. Bituminous coal usually contains a percentage of sulphur. This is what gives soft coal smoke its pungent odor. When combustion is complete, we find the product (SO_2), sulphur dioxide, in the chimney gases. If water vapor is present to any extent, we are likely to find the vapors of sulphurous acid, (H_2SO_3), or sulphuric acid, (H_2SO_4). The gas, sulphur dioxide, would be to a great extent dissipated in the air, but the acid vapors will invariably impregnate the soot, as well as descend of their own gravity. Surplus moisture in the gases tends to increase the output of acid vapors, and in this we have another argument against the use of the "steam jet." Coal itself contains more or less moisture, and a certain amount of sulphurous and sulphuric acid vapors are inevitable, but there can be no justification for such an increase of the evil as follows the use of the "steam jet."

We have been furnished with pretty accurate data as to the extent in which we may expect to find these acid elements present in ordinary coal smoke, and in soot deposits. Dr. R. Angus Smith, an English authority, tells us that .92 of a grain will be found in one cubic foot of smoke, if the coal contains as much as 1 per cent. sulphur.

Some very exhaustive experiments were made at Manchester, England, in 1891, to determine the extent of soot deposits and the proportion of sulphuric acid contained therein. Holly leaves were collected and the deposits which they carried analyzed. The figures given in the table below are in milligrams of deposit for each square meter of surface. The first samples were taken at Alexandra Park, a suburb, and succeeding samples taken at intermediate places between Alexandra Park and Albert Square, at about the center of the city. The table shows a rapid increase

SAMPLE TAKEN AT	SOOT	(H_2SO_4)
Alexandra Park	131	7.2
Owens College	315	10.4
Hulme	420	26.
Harpurhey	443	19.
Infirmary	728	27.5
Albert Square	833	24.2

of soot deposits as the center of the city was approached, and forms a good argument in favor of life in the suburbs as opposed to residence where smoke is more prevalent.

If the tongue is touched to a soot-covered surface, the presence of sulphuric acid will be indicated by a sour taste in the mouth.

Dr. Cohen, of Leeds, England, a number of years ago devoted a great deal of painstaking investigation to the subject of the atmosphere of cities. Some of his conclusions are interesting. He estimated that fully 20 tons of soot descended upon the city of Leeds every 24 hours. He found the soot to be loaded with ammonium sulphate and free sulphuric acid. He charges the vicious character of the fogs that at times prevail in great cities, notably in London, to the presence of soot and sulphuric acid. These fogs when breathed are accompanied by considerable irritation of the lungs and air passages. As to the presence of carbonic acid gas, Dr. Cohen says that the air of the large city contains one third more of this element than the air of the country. While carbonic acid gas is not poisonous to any extent, its presence in increased quantities means the displacement of a certain quantity of life-giving oxygen, while the lungs require all of the oxygen found in the natural state of the air.

There is certainly a marked difference between the atmosphere of the country and that of the city. The difference may be readily detected by the senses. The odds are in favor of country air, as there is no doubt that a smoke-laden atmosphere tends to an increase in mortality, especially with diseases affecting the nose, throat, and pulmonary organs.

It is impossible to estimate the damage resulting to health and property from the "chimney evil" in a city like Chicago, for instance, with an annual consumption of soft coal running far into the millions of tons. If any one doubts the extent of the Chicago smoke nuisance, let him ascend to the roof of one of the high buildings in the down-town district and look out upon the sea of erupting chimneys. The prospect will be suggestive of the inferno. "Looks like hell with the lid off," was the laconic observation of a visitor, coming from a locality where unadulterated air and sunshine are the heritage of everybody. He had expected, on ascending to the roof of the sky-scraper, that a panorama would unfold itself in every direction, extending to the city limits. A bowshot was about the extent of his vision.

A passenger upon a steamer approaching Chicago will, if the wind is right and atmospheric conditions favorable, be treated to a spectacular exhibition of the smoke nuisance that curses the city. The steamer will pass from an atmosphere of pure air and bright sunlight into a smoke bank so dense as to make the constant use of the steam siren necessary to avoid collision with other vessels.

That the dense and constant baptism of smoke afflicting Chicago and other large cities, leads to immense property loss cannot be disputed. It is idle to attempt to compute this loss, with anything like accuracy. One statistician with a gift for figures places the annual damage in Chicago at forty million dollars. Another, more conservative, places the annual loss at twelve million dollars. To police the city against this foe to health and despoiler of property, Chicago provides four smoke inspectors.

The damages wrought by the smoke nuisance are, or ought to be, so well understood that it seems superfluous to dilate upon them. They have been recognized ever since soft coal first made its appearance as an article of fuel. One Evelyn, in a pamphlet entitled "Fumifugina," published in the reign of Charles the First, attacked the nuisance as follows:

> "It is this horrid smoke, which obscures our churches and makes our palaces look old, which fouls our clothes and corrupts the waters, so that the very rain and refreshing dews which fall in the several seasons precipitate this impure vapor, which, with its black and tenacious quality, spots and contaminates whatever is exposed to it.
>
> "It is this which scatters and strews about these black and smutty atoms upon all things where it comes, — insinuating itself into our very secret cabinets and most precious repositories. Finally, it is this which diffuses and spreads a yellowness upon our choicest pictures and hangings; which is like Avernus to fowls and kills our bees and flowers abroad, suffering nothing in our gardens to bud, display itself or ripen, so that our anemones and many other choicest flowers will by no industry be made to bloom in London or the precincts of it, unless they be raised in a hot-bed and governed with extraordinary artifice to accelerate their springing, imparting a bitter and ungrateful taste to those few wretched fruits, which, never arriving at their desired maturity, seem, like the apples of Sodom, to fall even to dust when they are but touched."

Evelyn employed rather strong language, but he set forth

AUTHOR'S NOTE: Since this book was written, in 1906, Chicago has taken a position at the head of all cities in the war against smoke. The city now has what is probably the best organized smoke inspection department in the world.

the situation in something like its real colors. There are localities in Chicago, and doubtless in many large cities, where vegetation refuses to grow, on account of the poisons with which the atmosphere is laden. And in such an atmosphere of filth and poison, little children are born and reared, if they are so fortunate as to live, deprived of the pure air and sunshine that nature has provided for them.

The London *Lancet* asserts that the injuries inflicted by smoke on the health of the people of London are of greater consequence than the property damage.

An anti-smoke conference was recently held in London, and many interesting facts were brought out in the discussions; some of these facts are worth citing:

Upwards of a million tons of matter, heavily impregnated with sulphuric acid, are annually ejected into the atmosphere of London. Metals are corroded and statuary injured almost beyond redemption by the sulphuric vapors. Tapestries, frescoes, paintings, and other works of art are injured, and in many cases utterly ruined, by the soot and acid vapors, which penetrate everywhere. The employment of light colored building materials means a superfluous effort and expense. No building relying upon such features for its beauty can expect to retain them. Its face is daubed with the dun hue of London before the walls are completed.

Plants are killed by the soot deposits and the effects of the acids contained in them. Even when washed frequently they cannot attain to anything like their normal luxuriance.

It was estimated that upwards of one half of the sunlight is shut off from London by the great clouds of smoke and vapor that overspread the city like a vast umbrella.

Yet we are told that London has made great strides in the direction of smoke abatement as compared with American cities. No doubt London is in advance of many other municipalities in this particular.

It seems strange, when we consider how early the smoke nuisance came into prominence as a vital public question, that so little progress has been made in the campaigns against it. This may be accounted for, perhaps, by the tremendous demands for power to operate the machinery of this mechanical age.

Soft coal smoke was first recognized as an evil in England over six hundred years ago. The first smoke ordinance was far more stringent than any of its successors. During the reign of the first Edward, a statute was passed, making the consumption of "sea coal" a capital offense, the theory being that one good hanging would avail more with the offender than any number of fines. There was further agitation of the subject during the reign of Elizabeth. A proclamation was issued, making the burning of "stone coal" during the sitting of parliament an offense, as it was believed the smoke was injurious to the health of the Knights of the Shire. It was not, however, until 1785 that any sensible and concerted steps were taken in England in the direction of smoke abatement. A great deal was accomplished in London, Manchester, Leeds, and other cities in Great Britain, during the latter half of the last century, and the Englishman of to-day considers smoke abatement as one of the leading public questions.

More has been accomplished in Germany and France than in England. In Berlin the fireman is given a course of instruction under the supervision of the government, and great good results, both to the public through the decrease of smoke and to the consumer through the improvement in combustion. Paris insists upon the use of coke and other smokeless fuels as far as possible.

American cities contiguous to the anthracite coal fields are improving their atmospheres by the use of hard coal. The general use of such a fuel is, however, prohibitive for power purposes in most cities, owing to the cost. Anthracite, moreover, is not as well adapted for power as the bituminous coals. The city enjoying its general employment should not congratulate itself too freely on immunity from the "chimney evil," as large possibilities of danger are involved in the poisonous oxides that accompany its combustion.

Great as are the property losses inflicted upon the public by the "chimney evil," it is probable that financial losses almost as great are sustained by the owners of plants responsible for the smoke. The fuel losses arising from incomplete combustion have already to some extent been noticed. When we consider the coal consumption of Chicago, the losses which the smoking chimneys inflict upon their owners total in their probabilities up into appalling figures. The following statistics are considered reliable for 1905:

CHICAGO COAL RECEIPTS

	TONS
Anthracite, by rail	808,158
Anthracite, by lake	942,720
Pennsylvania, Bituminous	663,648
Ohio, Bituminous	594,851
West Virginia, Bituminous	933,117
Indiana, Bituminous	2,672,138
Illinois, Bituminous	4,012,752
Coke	463,710
Total	11,091,094

CHICAGO COAL SHIPMENTS

Anthracite	577,439	
Bituminous	2,095,671	
Coke	292,204	
Total	2,965,314	
Chicago Coal Consumption		8,126,780

The value of the coal consumed in Chicago in 1905 is estimated at $32,513,000. Taking the smallest percentage of probable loss, by reason of incomplete combustion, and applying it to these figures, we get a result in dollars wasted that will shock the economist.

We have noticed to some extent the difficulties that the steam boiler offers to the consummation of combustion. We will now devote ourselves to an inquiry into the means that may be employed to overcome these difficulties and minimize the losses sustained by the coal consumer.

Boiler-room economies have been largely neglected by the owner of the power plant, who has been exceedingly industrious in his search elsewhere for the economies, big and little. Practices are commonly permitted here, which, if duplicated in other departments, would soon put the concern owning the plant into bankruptcy. Why is it that the manufacturer will pay fabulous prices for machinery designed to reduce the cost of manufacturing an article the fraction of a per cent., and permit, without thought, fuel and other wastes to occur in the boiler room, which, if arrested, would reduce the manufacturing cost of the same article many times that fraction? The question will be left for some one else to answer. Our business is to show how these wastes, which we believe will be generally conceded, may be arrested and turned into profits.

The wastes that occur in the boiler room are chargeable to three sources:

1st. Improper equipment and installation. The architect designing the boiler room and surroundings, and the engineer designing the plant and specifying the equipment, are responsible.

2d. Improper and unintelligent handling of the furnace, the boiler and its accessories. The fireman and engineer are responsible.

3d. The use of a fuel that will not yield the maximum of heat energy at the minimum of cost. The purchasing agent, or whoever is charged with buying the coal and seeing that the article bought is delivered, is responsible.

With the first source of waste we cannot deal to any extent, as it involves too wide a discussion of engineering subjects. We will only say that crimes against good engineering are too commonly committed by the architect and designing engineer. The men in the boiler room must not be expected to carry on, with a high degree of efficiency, the nice chemical processes necessary to release the heat energy stored in the coal and convey it to the cylinder of the engine, if provided with equipment or tools, so inefficient or unsuitable as to render good results impossible. If the boiler plant and accessories are everything that could be reasonably expected, and a fuel is given the fireman, rich in ash and moisture and everything else except heat units, the best results are out of the question. A fuel should be selected that is adapted to the grates, draft, and general conditions under which the plant is operated. Some standard should be adopted for measuring the efficiency of the coal, — the net cost, for instance, of evaporating a thousand pounds of feed water. Trial runs on various grades of fuel will develop many facts as to availability of coal, and lead to the selection of a fuel best designed for the plant.

Assuming that the fireman is provided with the fuel best adapted to the furnace and boiler, let us look at the second source of loss, and see what steps can be taken to secure increased efficiency. In this case, the fireman is primarily the responsible party. The engineer is secondarily responsible, as it is a part of his business to see that correct practices obtain in the boiler room. Too low an estimate is usually placed upon the qualifications necessary to produce a good fireman. To handle furnace and boiler properly requires expert knowledge, reinforced by considerable experience. The fireman is in many respects the most important man about the plant. He stands at the very source and fountain head of the energy necessary to the plant, and conserves or wastes it. A premium should, and soon will be, placed upon his intelligence and efficiency. The Japanese government recognizes the truth of these statements. It pays as much attention to the education of the firemen upon its battleships as it does to training the men who handle the great rifles in the turrets. The man behind the shovel is recognized as standing behind the man behind the gun. It is due in no small measure to the Japanese firemen that the efficiency of Togo's squadron stands as a model for the navies of the world.

Now let us see what qualifications the fireman must possess, in order to satisfy the manager of the average steam plant. He must have sufficient muscle to enable him to shovel any required amount of coal. He must be sufficiently alert to watch the steam and water gages and see that they register properly, — that sufficient steam goes to the engine and that the boiler does not blow up. How he produces this steam, and how much coal he consumes in getting it, are matters that he is left to work out in his own way. Is he required to answer any questions about combustion and how to attain it with the greatest economy in a steam boiler furnace? Is he expected to know anything about the character or temperature of the escaping flue gases, — what these ought to be and how to secure them? Can he explain the various approved methods of firing, and does he know when and how to employ them? In Germany, the fireman is compelled to know something about these things. He is required to spend at least fifteen days under a government instructor, and pass an examination before he is given charge of a boiler. The German is proverbially thrifty and cannot view waste in the boiler room, or elsewhere, with complacency. When the owner of the American power plant fully awakes to the fact that the boiler room needs more attention, he will insist upon the same degree of efficiency and intelligence here that characterizes the typical American power and manufacturing plant in its other departments. Proper handling of the shovel will do much to increase efficiency, and just as much to abate the "chimney evil," but with boilers and furnaces as we have them the highest results are impossible, without the employment of some accessory to boiler or furnace.

An extended consideration of the third source of waste noted would be outside our province, — it will be left with the few suggestions already offered bearing upon it.

Little progress can be made with combustion studies in any power plant unless apparatus is employed to measure both the completeness and the efficiency of combustion. Complete combustion is not necessarily complete combustion. Many plants that never smoke at all evaporate less water per pound of combustible than other plants that are bad smokers.

Author's Note:—For a discussion of combustion testing apparatus, see Appendix.

CHAPTER V

SMOKELESS FURNACES IN GENERAL

There has been considerable discussion relative to the use of the term "smoke-consuming furnace," — some authorities maintaining that it is possible to "prevent" smoke, but impossible to burn it. Chas. Wye Williams, who was the inventor of a "smokeless furnace," and who wrote a book to advertise it, seems to have been the progenitor of the idea that smoke, once formed, cannot be burned. This doctrine has been preached to a great extent by engineering writers, and it will be found in the literature of a great many "smokeless furnaces." William Kent, in his "Steam Boiler Economy," says, "Smoke may be burned," and gives his reasons for this view of the matter as follows:

> "This last statement is contrary to that made by Chas. Wye Williams in his treatise on 'The Combustion of Coal and the Prevention of Smoke,' first printed about sixty years ago, and copied extensively by later writers, viz., that 'when smoke is once produced in a furnace or flue, it is as impossible to burn it or convert it to heating purposes as it would be to convert the smoke issuing from the flame of a candle to the purposes of heat or light.' The error of the statement made by Mr. Williams can be easily shown by a simple experiment which has been made by the author. A short piece of candle was placed inside of a tall, narrow tin cylinder. The deficient supply of air the candle thus received caused it to give off a column of black smoke. This was caused to pass into the central draft tube of a Rochester kerosene lamp, and as it passed up into the flame of the lamp it was completely burned, not a trace of smoke being visible in the lamp chimney. The experiment was also made with a still larger column of smoke, produced by burning paper under the lamp with the same result."

No less an authority than Professor Hutton of Columbia University takes the opposite view of the case, as follows:

"The term 'smoke combustion' or 'smoke burning,' is an improper one. Lampblack when once made is incombustible and cannot be burned."

Professor Hutton contents himself with this bare statement of alleged fact, and gives no reasons why carbon in the form of lampblack or soot is not combustible, while in other forms everybody knows it is highly so. The writer agrees with William Kent, that smoke is combustible, and that carbon in this form, given the right conditions, may be as readily burned as in any other. He is confirmed in this opinion by the following experiment, which is recommended to any one possessed of doubts as to the combustibility of soft coal smoke:

If a small quantity of coal, crushed to about the fineness of bird shot, is placed in the bowl of an ordinary clay pipe, the bowl of the pipe stopped with clay or otherwise and then heated to a point approaching red heat, smoke will issue from the stem of the pipe, and may be ignited, when it will burn with a white flame and with the entire absence of smoke. The flame may be blown out, and smoke will again issue. It will have the color and odor of the volatile coal gases, which escape from the chimney and is of the same character, with the exception that little or no carbonic oxide will be present, owing to the distillation taking place in the absence of air. The discharge of gas and smoke will continue from the pipe stem for some minutes, and when it ceases, the coal in the pipe bowl will be found to be coked. The process in the pipe bowl is quite similar to that which occurs in the retorts of gas works. It will be noticed that the smoke refuses to ignite until the pipe bowl approaches the point of red heat. If the pipe stem is heated to a similar degree, the smoke will burn, if ignited, the moment it begins to issue. Here we have another proof that heat is an important element in the combustion of smoke.

One of the earliest "smoke-consuming" devices invented consisted of two furnaces, in one of which the green coal was fired and the gases distilled or "sublimed." The smoke and gases were then conducted from this furnace to a point beneath the grates of a second furnace, carrying a bed of incandescent fuel. It was found that the smoke, in passing up through the fuel, was completely consumed.

Other devices were patented at an early date and some are on the market to-day, which return the smoke from the breeching or smoke-box of the boiler, mixing it with air and delivering it to the ash-pit of the furnace. The smoke, in such case, will burn in passing through the incandescent fuel on the grates. The writer considers it to be a well established fact that smoke, or the free carbonaceous element floating in the chimney gases, is combustible, and that the appellation "smoke consumer" is not a misnomer. Every farmer's boy knows that soot is combustible, and that the house chimney rids itself of this element by "burning out."

Before entering upon a discussion of the various classes of "smokeless furnaces," which will necessarily involve some criticisms, the author desires to state that all such criticisms are based upon the well-understood principles of combustion already set forth, and such practical facts as will be conceded by every well-informed engineer; the aim being to suggest such guides as will enable any one to select from the hundreds of devices upon the market, good, bad, and indifferent, that one which will be best adapted to the peculiar conditions obtaining in his plant. In the neighborhood of fifteen hundred United States patents are in force upon furnaces and other devices to promote combustion. It is obvious that these devices, if we are to make any pretense of covering the field, must be dealt with in groups or classifications, otherwise the task would be endless. A supplement to this book would have to be issued with every appearance of the Patent Office *Gazette.* The number of changes that can be rung on substantially the same thing, each one presenting some small feature of patentability, is truly astonishing.

What are the requisites of a good "smokeless furnace"?

1st. It must prove efficient as a "smoke consumer," no matter what grade of coal is used or what method of firing is employed.

2d. It must be capable of adjustment, by test and experiment, to meet all conditions of draft, coal consumption, etc., etc., — presented by any boiler, as no code of specifications can be drawn in advance to exactly meet the conditions in any given case.

3d. It must prove economical, — *i.e.*, increase efficiency and reduce coal bills. Improved efficiency should accompany improved combustion, but as has been shown this is not necessarily the case with a smoke-consuming furnace.

4th. It must act automatically and thus insure the very highest economy, without requiring constant attention and hand-manipulation by the fireman. The term, "automatically," is used with particular reference to the introduction of air into the fire-box, at such times and in such manner as will meet the changing conditions as to combustible gases.

5th. It must be low in cost, and within the reach of the owner of the small plant.

6th. It must prove durable and not require incessant repairs, with the incidental annoyance and expense of shutting down the plant at frequent intervals and inconvenient times.

No argument should be necessary to establish the fact that the above requisites are imperative. The necessity of air regulation has already been pointed out in connection with the diagram, Fig. 2, which illustrates the correct method of supplying air to the fire-box of a hand-fired boiler furnace, to meet the conditions. Such regulation should be automatic and independent of the will of the fireman, otherwise it might receive little attention and be of correspondingly little use. The imperative necessity of air regulation is conceded by all of the leading engineering writers, who have touched at all upon the subject. Many of them emphasize the fact that such regulation should be automatic. As long ago as 1843, the English engineer, Houldsworth, settled the importance of air regulation, by careful and exhaustive experiments. In these experiments, the air was regulated by "sight," which will answer in the case of a test, but would be out of the question in every-day practice, as it would necessitate the attendance of an experienced man at the dampers. Houldsworth assumed the efficiency of the boiler, all air excluded from the fire-box, as 100. He found, when burning Oldham coal, with constant air apertures of 35 square inches leading to the fire-box, that the efficiency was 94, and that when the air was regulated to meet the changing requirements of the gases, the efficiency was 114. With Clifton coal, he found that the efficiency with air regulation was 135.

Excess air, strange as it may seem, leads to an increase in stack temperature, — the surplus air more readily taking on the heat of the gases, through which it is passed, than the heating plates of the boiler will absorb it. M. Burnat, of France, gives the following results illustrating the increase of stack temperature as the excess of air increases:

CUBIC FEET OF AIR AT 62° FAHR. PER LB. OF COAL	AVERAGE TEMPERATURE OF GASES LEAVING BOILER FLUES
272	624
196	601
168	550
124	487

"Smokeless furnaces" may be variously classified, — such division being largely an arbitrary matter. The author has, for purposes of convenience, adopted the following classification:

- I. Mechanically Fired Furnaces
  - 1. Underfeed Stokers
  - 2. Overfeed Stokers
    - (*a*) Horizontal Moving Grates
    - (*b*) Inclined Movable Grates
    - (*c*) Fuel Spreaders
    - (*d*) Pulverized Fuel Burners
- II. Hand-Fired Furnaces
  - 1. Mechanical Draft
    - (*a*) Air Blowers
    - (*b*) Steam Blowers
  - 2. Natural Draft
    - (*a*) Steam Jet Auxiliaries
    - (*b*) Air Furnaces
      - 1. Grate Admission
      - 2. Fire-door Admission
      - 3. Side-wall Admission
      - 4. Bridge-wall Admission
      - 5. Arch Admission
      - 6. Miscellaneous
    - (*c*) Fire-arch Furnaces
    - (*d*) "Dutch-oven" Furnaces
    - (*e*) "Down-draft" Furnaces

The attention of the reader is redirected to the following facts, which are vital, and must be borne in mind when considering the merits of any device, claiming to assist combustion and increase boiler or furnace efficiency:

There are three prime requisites to the combustion of the gases discharged in the fire-box: 1, a sufficient supply of free air in the fire-box and intermixed with the gases; 2, a sufficient temperature at the point and moment of ignition; 3, sufficient room for the expansion of the burning gases during the act of their combustion.

There are other requisites, secondarily essential, which will be noticed as the discussion proceeds.

CHAPTER VI

MECHANICAL STOKERS

The mechanical stoker is by no means a recent invention, and there is little that is new, except mere detail, in connection with any mechanical stoker now on the market.

The idea of mechanically supplying the coal to the furnace seems to have first occurred to Wm. Brunton in 1819. He patented a circular fire grate, movable on a vertical spindle.

John Stanley, in 1822, patented means for blowing the coal upon the grates by means of a fan.

J. G. Bodmer, in 1834, patented the first movable grate. The bars were made to move toward the rear of the furnace, where they dropped singly upon rails and were mechanically returned to the front.

John Juckes, in 1841, patented the first "endless chain" grate.

Samuel Hall, in 1845, was the first to introduce reciprocating inclined grate bars in connection with a mechanical stoker.

T. and T. Vickers, sometime in the forties, invented the first "under-feed" stoker, employing a ram to place the fuel in position. This machine was called in ridicule "a sausage stuffer," and the term has clung to this type of stoker ever since.

John Bourne, about 1857, was the first to introduce the idea of reducing the coal to a fine powder, and blowing it in a dry state into the fire-box, mixed with air, where it was supposed to burn, much after the manner of gas.

UNDERFEED STOKERS

In the under-feed type of stoker, as we have it to-day, the fresh coal is forced by mechanical means from below, up into the bed of burning fuel. A steam ram is employed for this purpose. Air is supplied by a fan and is delivered in jets into the green fuel, the theory being that the volatile gases distilled from the green coal by the influence of the heat of the burning fuel above are mixed with the oxygen supplied by the air jets, and burn on their passage up through the incandescent coal. There is no doubt that such an effect takes place. The coked fuel above supplies the heat, and the air jets the necessary oxygen. Stokers of this type will produce the best efficiency when they are operated with as little vacuum as possible in the fire-box. The fireman usually sets the damper wide open, putting the full draft of the stack upon the furnace. With the chimney pulling and the forced draft pushing, the efficiency will be low. The author recalls one case where the vacuum in the fire-box was reduced from 55 hundredths of an inch to 10 hundredths. This was followed by an immediate reduction in the fuel consumption of more than 30 per cent. It often happens that seams and cracks are formed in the upper strata of fuel, when the green coal is rammed into position below. Under such circumstances, the volatile elements will escape and there will be smoke. Until the fuel settles into position, closing the cracks, there will be, of necessity, some escape of free air into the fire-box. The time and extent of feeding fuel may be in the control of the boiler attendant, or they may be automatically regulated by the boiler pressure. Clinkers are likely to form to a considerable extent, near the point of air delivery, and also upon the dead plates which are employed in place of grates. Such clinkers must of necessity be removed by hand, as in the case of the hand-fired furnace. This constitutes one of the main objections to the under-feed stoker. The under-feed device has both advantages and disadvantages, as compared with other styles of stokers on the market.

OVERFEED STOKERS—THE "CHAIN GRATE"

Among over-feed stokers employing horizontal moving grates, the "endless chain grate" type seems to predominate, almost to the point of excluding all others. The coal is usually fed from a hopper upon the grate, at a point slightly forward of the boiler front. An arch of firebrick or tile is generally provided over the forward end of the grate. This arch becomes highly heated, and the reflected heat first distills the volatile gases from the fresh coal, and also assists in igniting the fuel. The fuel is carried slowly to the rear by the moving grate, passing through the various stages from distillation of the volatile elements to final combustion of the fixed carbon. Advocates of this style of stoker talk at great length about "progressive combustion," a term which does not necessarily carry any practical significance, as all combustion is obviously "progressive." It is of great importance to the owner and operator of a chain grate stoker that this "progressive combustion" take place in proper concord with the movement of the grate; otherwise, one of two extremely undesirable things will occur. The ash is dumped into a pit at the rear when the chain grate makes its downward turn. It is evident that if combustion is not fully completed when the dumping moment arrives, unconsumed fuel will be deposited along with the ashes and a direct loss will result. It is also evident that if combustion is completed before the dumping moment arrives, the grate will be bare in places and cold air will rush in and affect efficiency. To adjust the feed and time the speed of the grate in such a manner that combustion is fully completed at the moment of dumping, and not before, is a nice proposition and requires a high degree of vigilance, experience, and expertness. It is possible, moreover, for the two undesirable results mentioned to occur simultaneously. There will be some friction between the fuel on the grate and the side walls of the furnace. This will tend to retard somewhat the movement of the fuel that is under the influence of the friction. What may, for want of a better term, be called the "fire line" — the line where combustion is completed — will very likely be irregular, unconsumed fuel being dumped into the ash-pit at one or more points and air being allowed to enter through bare spots at others. Boilers equipped with such stokers are usually set detached or semi-detached, and a door provided at the side about midway of the grate. This door gives access for the fire tools of the attendant, whose duty it is, among other things, to attend to the fire line, keep the same regular and at the proper distance from the dumping point. The attendant must also increase or diminish, or entirely stop the movement of the grate, as occasion requires, in order to keep the fire line in the proper position. It is necessary for the man charged with these duties to remain awake.

Considerable opportunity is always present for the leakage of air into the fire-chamber. There must be room for "play" between the moving chain grate and the side walls of the furnace. This free space will probably be covered with fuel throughout a portion of its length, but toward the rear of the fire-chamber the fuel will tend to work away from the side walls, leaving an opening that air will be bound to find. Unless suitable provision is made against it, air will find its way around the rear of the grate and up into the fire-chamber. Some air is of course necessary to the burning gases, and if these leaks that we have pointed out could be properly proportioned to the demands of the fire-box, there would be no objection to them.

It is argued by the manufacturers of chain grate stokers that the use of their devices results in a large saving of labor. The testimony of the boiler room will not always bear out this contention. It requires almost as much muscle to get the coal into the hopper of the stoker as would be required to feed the ordinary hand-fired furnace. This criticism of course does not fully apply if the coal is gravity carried to the stoker from a point overhead. The chain grate is somewhat narrowly limited as to the character of the fuel that may be successfully burned. If screenings or nut coal are unavailable, a coal crusher must be employed. There is almost invariably and unavoidably a serious leakage of fresh coal through the grate, not to mention a further leakage of partly burned fuel. The green coal is fed upon a bare grate, and something of a sifting process occurs. The chain grate is made up of a multiplicity of small members, and to avoid cramping at the turns a freedom of movement between the grate members is provided for, which sometimes results in more air space than good practice demands. Such superfluous air space in the grate does not tend to minimize the loss of coal. A deep pit is provided beneath the grate and the men in the boiler room are well acquainted with it, if the engineer in charge makes any pretensions as to economy. This pit requires frequent shoveling out and the mixture of coal, cinders, and ashes is "burned over." Notwithstanding any number of "burnings over," the final ash from a chain grate will usually contain some surprises in the way of combustible.

INCLINED GRATE STOKERS

This type of stoker is furnished with an inclined grate surface, — the inclination sometimes extending from the sides toward the center, and sometimes from the front to the rear. The grate members are usually given a reciprocal motion, which is designed to work the coal from the hopper to the ash-pit at the bottom, as combustion proceeds. Sometimes this movement of the coal is faster than desirable, — "landslides" occur, exposing the bare grate and filling the ash-pit with unconsumed fuel. Sometimes the coal is perverse and refuses to descend, adhering to the grate bars so tenaciously that the vigorous use of a slice bar is required to detach it. It is claimed for this type of stoker that more grate surface can be provided in proportion to the heating surface of the boiler than with any other, making an increase of horse-power possible, if desirable. All types of stokers are more or less limited as to quality and character of coal, the type under consideration particularly so, as any fuel disposed to melt down, or "slag," will tend to adhere to the grates, while a fuel of the opposite extreme will be subject to "landslide."

FUEL SPREADERS

The "fuel spreader" is an uncommon type of stoker, and is not entitled to very serious consideration. The coal is projected upon the grates, sometimes continuously and sometimes at intervals, depending upon the means employed and the ideas of the inventor. A mechanism is sometimes employed to project the coal, and other variations of the idea make use of a jet of steam, drawn from the boiler. The "fuel spreader," like other stokers, has its limitations as to character of coal employed.

PULVERIZED FUEL BURNERS

The pulverized fuel burner has so far failed to score very much of a success. Coal, finely powdered and mixed with air, is instantaneously combustible to the point of being explosive. If delivered to a furnace in jets, or otherwise, properly mixed with oxygen, it will burn, much after the manner of a combustible gas. The difficulties in the way of such a device appear to be principally of a mechanical and practical nature, and the inventor may yet be forthcoming who will solve them. The writer knows of nothing of the kind at present, sufficiently well demonstrated along practical lines, to warrant serious consideration by the coal consumer.

Author's Note: Since this book was published in 1906 the "fuel spreader" has been developed into a practical device.

AS TO STOKERS IN GENERAL

The mechanical stoker unquestionably has its field, and has no doubt entered the engineering world to stay. The best of such devices is, however, far from the pinnacle of perfection, and the purchaser will do well to investigate the field carefully before buying. The initial cost is necessarily heavy, and the cost of maintenance is an item to be gravely considered. If mechanical means are provided to get the fuel into the hopper of the stoker, a considerable saving of labor will result. If the shovel is relied upon, the small saving of labor effected will be fully offset by the increased care necessitated in order to insure anything like fair results. The limitations as to quality of coal are factors to be taken into account. Most stokers are designed to burn "slack" or "screenings," and while these grades of coal are usually obtainable, when desired, it is not to be assumed that they invariably will be. As a matter of insurance against shut-downs for want of suitable fuel, the plant employing mechanical stokers should be equipped with a coal crusher.

CHAPTER VII

HAND-FIRED FURNACES — MECHANICAL DRAFT

MECHANICAL draft has, under many circumstances, much to recommend it. Under certain circumstances it is almost a necessity, — as for instance when anthracite coal, particularly dust, is burned for power purposes, or when great increase of horse-power is necessary, irrespective of efficiency. Mechanical draft, when applied to a boiler furnace, may be either "forced" or "induced," *i.e.*, air may be forced by fan or otherwise under the grates, the ash-pit doors being sealed; or the contents of the breeching may be exhausted and draft "induced," the atmospheric pressure supplying the increased draft in its effort to fill the vacuum. The increased oxygen supplied by either means greatly hastens the consumption of coal and increases the available horse-power of the boiler, though not necessarily in proportion to the increased coal consumption. It is, of course, fully as necessary to supply air to the gases in the fire-box when mechanical draft is employed, as in the case of natural draft. If such air is not supplied, combustion may be just as incomplete as under any other circumstances. Where mechanical draft, especially forced draft, is employed, a surplus of air may be expected to find its way through the fuel on the grates, and this surplus is often sufficient to supply the needs of combustion. If efficiency is had in mind, the difficulty at once arises of keeping such air supply down to the needs of the fire-box. If the demands are exceeded, waste of heat units is bound to result. The ideal system of mechanical draft will deliver a portion of the air supply above the fire, and this portion will be under automatic control to meet the general conditions in the fire-box, set out by the diagram, Fig. 2. Where such arrangement is in effect, sufficient fuel should be carried upon the grates to insure the absence of air holes. Some power is of course necessary to accomplish mechanical draft, but this outlay of energy may be more than offset by employing the waste heat of the escaping gases for some practical purpose. Temperature in the chimney is necessary where natural draft is relied upon, as the temperature is the cause of the draft, but in the case of mechanical draft, such temperature, while it may be of assistance, is not necessary. Advocates of mechanical draft lay great stress upon the claimed saving in installation, as against a natural draft plant. This saving is effected by the smaller chimney required. Mechanical draft can get along without any chimney at all, if necessary, while with natural draft the chimney is one of the principal items of cost. It should be remembered that a chimney, if properly built, will last indefinitely, and is not subject to depreciation, while the same cannot be said of the machinery incident to any system of mechanical draft. The chimney, if carried high enough and properly proportioned, will produce any amount of draft desired. Public health demands a high chimney, as it is advisable to discharge the gases resulting from combustion, as high up into the air as possible. The smoke from a tug-boat or locomotive does more damage to health and property than that discharged from a factory chimney, and municipal regulations should, among other things, insist upon high stacks. With the small steam plant, there is no doubt that cost of installation, adequate chimney included, is in favor of natural draft. There is room for so much argument pro and con of mechanical draft, so many factors entering into the situation, that the owner of the power plant will do well to give the subject most careful consideration before abandoning natural draft.

Jets of steam are sometimes employed for the purpose of assisting draft. The cost of installation in such case is very light and constitutes the only argument in its favor. The steam required to operate such a device to any degree of efficiency as a draft accelerator represents an expenditure for fuel far in excess of the interest charge on the cost of equipping the plant with a fan-blower system.

All those devices which return the escaping smoke to the fire-box or ash-pit, for the purpose of consuming it, must be considered under the head of mechanical draft. It is difficult to imagine a sane argument in support of the use of such a device, smoke consumption being in mind, when the market affords others capable of consuming the smoke and gases before they leave the combustion chamber. If it can be shown that the return to the fire-box of a portion of the gases carried by the breeching tends to lower the temperature of the gases in the chimney without affecting the rate at which coal may be burned upon the grate, and if the amount of saving represented by such lowering of stack temperature exceeds all the costs that may be legitimately charged against the operation of such a device, then there are good arguments in its favor. The author recently inspected a device of the kind under consideration. The engineer of the plant presented very satisfactory evidence that he was saving fuel as well as reducing smoke. The saving was partly attributable to the burning of the combustible gases returned but mainly attributable to the use of the heated oxygen returned with the gases. A considerable surplus of air was being passed through the furnace. This meant considerable highly heated oxygen in the flue gases, which on being returned to the furnace reduced the requirement for fresh air, thereby reducing the excess air. Efficiency was increased as the air excess was reduced and the heat units returned with the flue gases were just that much gain. There are certain types of boilers, to which such an arrangement might be well adapted,—an internally fired boiler of the marine type for instance, which, owing to its construction, prohibits the use of any arch or other accessory to the furnace proper, to aid in combustion. It has been proposed by several inventors to absorb the heat of the escaping gases by a system of air pipes within or a box arrangement about the breeching,—the air heated in this manner being supplied to the furnace by a blower. Such plan has, in fact, been employed with gratifying results. A French inventor carried it to the extreme by taking his air supply from near the top of the stack and conducting it through a sheet metal flue down the chimney and through the breeching to the boiler furnace. It is quite needless to say that the Frenchman's plan proved impractical.

NATURAL DRAFT

Most "smokeless furnaces" are to be found in the field of hand-fired boilers employing natural draft. This is necessarily the case, as such boilers largely predominate and always will be in the majority. The salesman for the mechanical stoker and mechanical draft appliance finds his most fruitful field among large power plants making new installations. These plants are vastly in the minority, and greater popular interest attaches, accordingly, to the field we are about to consider, which interest provides excuse for the more extended notice of the devices peculiar to this field.

"STEAM JETS"

It is impossible for the author to give honest expression to any views favorable to the use of the "steam jet." Such a statement, at the outset, necessitates a close examination of these devices.

"Steam jets," by a wide margin, constitute a majority of the devices to regulate smoke and improve combustion, upon which the United States Patent Office has issued Letters Patent, since the smoke problem began to claim the attention of the inventor. Scarcely a week passes that does not see an increase in the brood. It is hard to find a boiler in Chicago, in service for any length of time, that has not had experience with one or more of these makeshift appliances. It is hard to find language sufficiently acrid to do justice to the "steam jet," for its use constitutes a crime against good engineering. Something may be said in favor of almost every other class of smoke-consuming appliance, but the writer is unable to discover a single redeeming feature in the whole horizon of "steam jets." If such redeeming feature exists, it lies in the low initial cost of such an appliance. No doubt this item of low cost has had much to do with the wide-spread use of this type of "smoke consumer." It must be admitted that the use of a "steam jet," if properly applied and operated, will tend to satisfy the smoke inspector; its effects upon combustion, however, as a flue gas analysis will show, are counterfeit and consist more in appearances than actuality. The cost of supplying the steam to operate such a make-believe appliance is so great that the man who pays the coal bill could not afford its use, if paid handsomely to permit the equipment of his boilers. It is obligatory upon the writer to furnish very valid reasons for the employment of such sweeping criticisms.

Objections to the use of a "steam jet" may be catalogued as follows:

1st. The cost of supplying steam to operate such a device is prohibitive.

2d. The steam introduced absorbs heat, and lowers, to the extent of such absorption, the efficiency of the boiler.

3d. If directed against the fuel bed, escaping carbonic acid gas is reactively converted to carbon monoxide, and heat is absorbed in the operation. Carbon monoxide is also directly formed by contact between steam and incandescent coke, and unless free oxygen is admitted to the fire-box, this gas escapes, entailing a further loss. The conversion of carbon monoxide in this manner entails a loss of heat, and the water vapor resulting from the reunion of the released hydrogen of the steam with oxygen absorbs still more heat. The released hydrogen also combines with carbon to form marsh gas, and such combination absorbs heat.

4th. The floating soot in the smoke is precipitated and deposited upon the shell and tubes of the boiler in the form of scale. Such scale is impregnated with sulphur, and "pitting" of boiler shell and tubes is likely to occur.

5th. Escaping oxides of sulphur are converted to vapors of sulphurous and sulphuric acid.

6th. The grates are robbed of draft, clinkers, and burned out grate bars result.

7th. The noise attendant upon the use of a "steam jet" is almost insufferable.

8th. The use of "steam jets" may impair efficiency to such an extent that additional boiler capacity, boiler room, and labor will have to be provided.

Let us see how far this catalogue of objections can be substantiated:

If the engineer who is employing a "steam jet" believes he is using a negligible amount of steam for the purpose, let him condense the steam from the jets for a day and weigh the resulting water. Then let him divide the quantity of water taken by his boiler during the day into the result, and treat himself to a surprise. It is only by such tests as these that we can arrive at the extent of losses and savings in an intelligible manner. An offhand estimate is never reliable.

In 1890, tests were made at the United States Navy Yard, Brooklyn, New York, to determine the efficiency of various patented steam jet devices offered the government. The tests were conducted by the chief of the Bureau of Engineering of the United States Navy. The steam to operate the jets was drawn from a separate boiler, used for the time being for no other purpose. It was found that the jets consumed steam amounting from 8.2 per cent. to 21.2 per cent. of that generated by the boiler to which they were applied. The steam from one of the jets, having a nozzle one sixteenth of an inch in diameter, was condensed and a pound of water resulted in two minutes. This is almost equivalent to one horse-power. Steam is usually conducted from the boiler to the jets through a pipe not less than one-half inch in diameter. If enough jets are employed to equal the capacity of the pipe, as is often the case, the loss entailed is quite a formidable matter.

The writer knows of many cases where tests have been made to determine the amount of steam consumed by jet devices, and in no instance has such consumption been less than 10 per cent. of the generated horse-power of the boiler. The figures average nearer 15 per cent. if the jets are operated to the extent of having any appreciable effect upon the appearance of the smoke.

The Chicago *Tribune*, in reporting an address delivered by Chief Smoke Inspector Schubert of the Chicago Boiler Inspection Department, at a banquet of the Commercial Club, says:

> "He criticised 'steam jets' as makeshifts, and advised against their installation, as they consume from 10 to 15 per cent. of the steam generated, for their operation."

That the use of a "steam jet" entails a serious loss of power, is a fact so easily ascertainable by any one interested, that further discussion would be superfluous.

The second criticism offered above should require no argument for its substantiation. Steam is not combustible, neither does it in any way aid in combustion, when supplied in this manner. It must be heated to the temperature of the escaping gases and such an operation results in the absorption of heat units and a corresponding lowering of the efficiency of the boiler. It is undeniable that steam is composed of hydrogen and oxygen, that hydrogen in its free state is a highly combustible gas, containing approximately 62,000 British thermal units per pound; that oxygen is the supporter of combustion and the fire will flourish when oxygen is present; and that water or steam may be decomposed into its elements in the fire-box. It does not follow, however, as many advocates of "steam jets" fondly believe, that any gain of heat units can result from the burning of the hydrogen, decomposed in the fire-box from its union with oxygen. Berthollet's Second Law applies, as we have already pointed out. As much heat is absorbed in the decomposition of the steam as is generated by burning the hydrogen after decomposition occurs. The product of the combusion of hydrogen is water. If hydrogen could be injected into the fire-box in its free state and without drawing upon the heat of the furnace for its isolation, the proposition would be an entirely different one. All "water gas" arguments advanced in favor of "steam jets" may accordingly be dismissed as entirely unworthy of consideration.

In connection with the third criticism upon "steam jets," we would revert to the report of Eckley B. Coxe, published in the transactions of the New England Cotton Manufacturers Association, previously noticed. The result of Coxe's tests upon the "steam jet" bears out the contentions of the author in his third criticism, and also stands in proof of what has been said concerning the relative efficiencies of the fan and steam blower system of mechanical draft. Now let us see how the chemical reactions claimed under the third head occur, when jets of steam are directed into the fire-box. More or less carbonic acid gas will be escaping from the incandescent fuel. If the jets are directed against the fuel, this gas, (CO_2), will be forced back into the carbon, where it will pick up another atom of that element, and (C_2O_2), or (CO), carbon monoxide, will result. This reactive formation absorbs heat as the tendency is away from instead of toward combustion or oxidization. If a jet of steam is directed against coke at a low red heat, practically pure hydrogen and carbonic acid gas will result, — the reaction being as follows:

$$2\ (H_2O) + C = 2\ (H_2) + (CO_2)$$

If, however, the coke is incandescent the reaction is somewhat different and is as follows:

$$(H_2O) + C = (H_2) + (CO)$$

The following reaction may also result from the union of the released hydrogen with carbon:

$$2\ (H_2) + C = (CH_4)$$

The formula, (CH_4), stands for marsh gas, or light carburetted hydrogen. All the above formations represent ab-

Author's Note: The reaction of incandescent carbon upon CO_2 is usually expressed by the following equation:

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

It is not positively known how the steps in this reaction proceed. It has been held by some chemists that an unstable molecule (C_2O_2) is formed, which is at once broken down into two molecules of CO.

sorption of heat, and the efficiency of the boiler is lowered by the extent of such absorption. If these gases are burned by the admission of free oxygen, the absorbed heat is of course restored, but no net gain to the boiler can be argued from the combustion of any gases so formed. All of the above contentions will be substantiated by any standard authority on chemistry.

As to the fourth criticism, the following is offered: It often happens when coal, particularly dry "slack," is shoveled into the bin, that the dust is almost unbearable. The engineer or fireman turns a jet of steam into the bin, and the loose dust or carbon floating in the air is moistened by the steam vapor and is settled or precipitated to the floor. The effect of a "steam jet" upon the loose soot or particles of carbon floating in the furnace gases is the same. It is precipitated upon the shell and tubes of the boiler in the form of "scale." The writer has seen scale a quarter of an inch thick in the fire-tubes of a tubular boiler, due to the use of a "steam jet." The scale was so hard and tenacious that nothing short of "reaming" sufficed to remove it. It was found upon examination that the tubes were corroded to the danger point by the action of the sulphur compounds contained in the scale, and every tube in the boiler was condemned and removed. There had been large diminution in the draft of the boiler in question, and this diminution was correctly charged to the reduced area of the tubes, due to the scale. Some inventors of "steam jet" appliances are honest enough to call their devices "smoke bleachers" or "washers," and such appellations are well chosen. Observe the effect when the wind is in the right direction to blow the steam from the exhaust funnel at the top of the building into the smoke issuing from the stack. The black carbon will to a greater or less extent be "washed out" of the smoke. Every one has noticed that there is less color in the smoke when a locomotive is running under steam than when the steam is shut off and the engine is slowing down. This is due to the fact that the steam exhaust discharges into the smoke-stack.

As to the fifth criticism, little need be said in support of it. All bituminous coal contains more or less sulphur. When this element is oxidized, the product is sulphur dioxide, (SO_2). This is a gas, but it is soluble in water, and when it encounters steam or water vapor under the boiler or in the chimney gases, the following reaction, resulting in sulphurous acid, occurs:

$$(H_2O) + (SO_2) = (H_2SO_3)$$

If another atom of oxygen is added, the result is (H_2SO_4), or sulphuric acid. Everybody knows what sulphurous or sulphuric acid will do to iron or steel. There is more or less moisture in all grades of soft coal, and more or less water vapor entrained in the atmosphere. Some sulphurous or sulphuric acid is, accordingly, unavoidably formed. It is bad practice to multiply the evil by blowing unnecessary moisture, in the form of steam, into the furnace gases.

With reference to the sixth criticism, it need only be said that the boiler flues, breeching, and stack are forced to accommodate the steam delivered to the furnace by the jet, and to the extent of the volume of such steam the draft of air through the grates is diminished. If sufficient steam is introduced to have an appreciable effect upon the color of the smoke, the impairment of draft will be such as to work damage to the grates. If the steam is not turned off, either by hand or otherwise, between firings, the damage resulting to grates will be still more aggravated. It is often urged, and with some reason, that the use of a "steam jet" tends to a softening of the clinkers. Substantially the same softening results will be attained if the ash pit is kept supplied with a quantity of water. Draft impairment means clinkers, and anything beyond a moderate use of the "steam jet," means draft impairment. The "steam jet" will do well if it succeeds in softening the clinkers for which it is itself responsible.

Every one who has seen a "steam jet" in operation will agree that the seventh criticism is well taken.

Acceptance of the eighth objection follows upon admission of the correctness of the preceding criticisms. If, for instance, the plant is equipped with ten boilers, all supplied with "steam jets," and the consumption of steam to operate the jets is 10 per cent., then the plant has the effective horse-power of nine boilers, and if this is not sufficient, additional boilers will have to be provided. "But," the advocate of the "steam jet" may argue, "we have increased the horse-power of the boiler since equipping it with the 'steam jet' device." If the steam should be delivered exclusively above the grates, such statement could have no foundation in fact. If the delivery should be below the grates, forced draft would result to some extent and increased horse-power might occur. Any such increase of horse-power would necessarily be attended by a decrease in efficiency to the extent of making the increased power a very expensive matter.

All of the authorities are in agreement with respect to the undesirability of the "steam jet." One or two will be quoted. Walter B. Snow, in his "Steam Boiler Practice," says:

> "The case of the 'steam jet' may be briefly summarized thus: It has the advantage of costing very little to put in and keep in repair. Its disadvantages are, first, it requires a very large amount of steam to run it; second, it introduces a large amount of water or steam, all of which has to be heated and carried up the chimney; third, unless very carefully managed there is a large development of carbonic oxide (CO), hydrogen, and marsh gas, due to the dissociation of the water, which has a tendency to carry off a great deal of heat in the stack; fourth, the intensity of draft produced by this means is distinctly limited; and fifth, the noise incident to its use is at times excessive."

D. K. Clark, a well-known British engineering author, who was himself the inventor of a "steam jet" apparatus, is forced to conclusions unfavorable to the use of such a device. With respect to a test made upon his own contrivance, he tells us that the evaporation was 7.35 lb. of water with the jet in operation, and 7.10 with the jet off. He does not tell us what amount of steam the jet consumed in its operation. It certainly must have been far in excess of the slight gain in evaporation, which could be accounted for, perhaps, by atmospheric conditions or other agencies having no connection with the device.

The same author tells us of a "steam jet" device patented by M. W. Ivison in 1838, which was discredited after careful tests, as wasting fuel, although it was conceded smoke was "stopped." He tells us also of tests made upon a device patented in 1858 by M. Emil Burnat, a French inventor. In this case, "smoke prevention" was complete, but the efficiency was lowered 8 per cent.

An examination of the United States Patent records develops the fact that over 75 per cent. of the patents issued in the last seventeen years on "smoke-consuming" appliances have been granted on modifications of the "steam jet." The inventor has blown steam into every conceivable part of the furnace, combustion chamber, smoke-box, breeching, and chimney. The most common form of the "steam jet" is illustrated in Fig. 5. Other points of steam admission, preferred by various inventors, are indicated by the letters "a," "b," "c," etc. Less objection, of course, attaches to the introduction of steam into the breeching, or chimney, as compared with points preceding the escape of the gases from the boiler. Soot, and scale deposits, will do less damage to the breeching and stack than to the shell and tubes of the boiler.

Air is often blown or "siphoned," as the inventor usually expresses it, into the fire-box by a "steam jet," and the air in such case naturally assists in combustion. The nearer such combination device comes to relying upon the agency of air, and the further it gets away from the use of a jet, the less objections there are to it. The objections become still fewer in number when the use of the jet is discarded altogether. Many "steam jets" employ an automatic mechanism to turn on the steam when the furnace is stoked and turn it off again after a certain period elapses. Such an arrangement of course tends to make a bad matter a little less obnoxious. If the jet is not constantly in use, the tip is liable to be fused over and the engineer has an unnecessary annoyance added to his list of troubles, most of which are unavoidable.

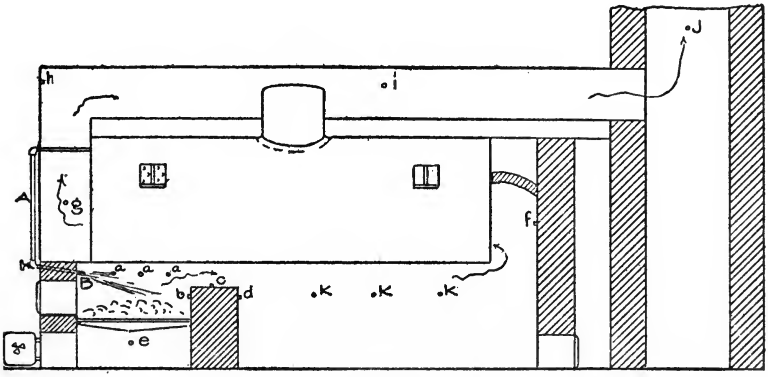


FIG. 5

The writer dismisses the "steam jet" with the feeling that a disagreeable duty has been honestly performed in the interests of good engineering.

AIR FURNACES

The term "air furnaces," which is of the author's own coinage, is meant to include all those devices, applicable to hand-fired boilers employing natural draft, which introduce air into the fire-box or elsewhere beyond the grates, for the purpose of promoting the combustion of the gases originating from the fuel. What has been said concerning the necessity of "air regulation" applies impartially to all the various types of devices that remain to be considered. No device should be considered by the coal consumer unless it is equipped with means to accomplish such air regulation. No air regulating mechanism can be considered as meeting the conditions, moreover, unless it is "adjustable" by experiment to meet any combination of conditions that may result in a change of demand as to air, either in quantity or in manner of admission. The broad statement may be safely made that improved combustion, coupled with proper air regulation, means an increase in efficiency, — the extent of such increase being determined by the extent of the improvement in combustion; while improved combustion, even to the extent of burning the last atom of the combustible, may, and probably would be, attended by a loss of efficiency in the absence of proper regulation of the air admitted.

GRATE ADMISSION

The difficulty of introducing the proper amount of free oxygen to the fire-box through the grates has already been pointed out. Some air furnaces employ what is known as the "alternate" system of firing. One side of the furnace is fired with fresh fuel, and the heat of the incandescent fuel on the other side is relied upon for "temperature," it being expected that sufficient free air will find its way through the partly burned out bed of coke, to supply the necessary oxygen to the combustible gases released from the fresh fuel. It is manifest that if air is to be supplied in this manner, a degree of care and expertness must be employed in stoking, not usually encountered in the fire-room. It is also evident that more air will be admitted as the fresh fuel approaches the coking point where the demand for oxygen is small, than immediately after firing when the demand is at the maximum. The longer the coked fuel remains without the addition of fresh coal, the more opportunities the air will find to work its way through it. There are many practical reasons why such an arrangement for air admission is not the ideal one, although it has, in connection with the method of firing necessarily employed, much in its favor. It is impossible, however, to approach anything like correct air regulation, with a furnace of this character. The scale of air admission will be the reverse of the correct one as indicated by Fig. 2, and the fireman would be indeed fortunate if able to so regulate the fuel bed that the same quantity of air would be admitted at each firing.

Hollow grate bars were early employed for air admission, the air being sometimes delivered from the front end of the grates near the dead-plate, and sometimes from the rear, through the bridge wall. The idea of the inventors of such grates seems to have been that the air would be to some extent superheated in passing through the hot grate bars.

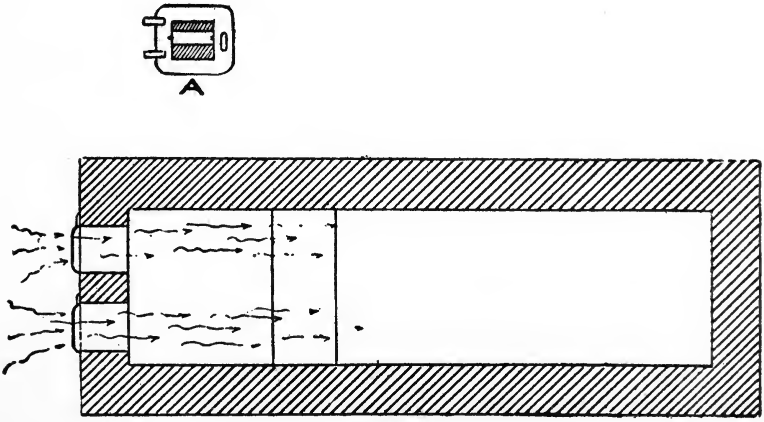


Fig. 6

FIRE-DOOR ADMISSION

J. J. Roberton, of Glasgow, seems to have been the first to supply air to the fire-box by way of the fire-doors. He patented a special door for that purpose in 1800. He supplied the coal to the furnace by means of a hopper. It was allowed to coke in the front of the fire-box and was then pushed back to the rear.

Fig. 6, showing a horizontal cross-section of a furnace and boiler setting, will serve to illustrate the objections that may be advanced against this manner of air admission. The opportunities for thorough admixture of the air with the gases are not what they might be, if admission is after this manner. The air enters in substantially an undivided stream, which bores its way through the gases of the fire-box. If the door should be provided with a "grid," the air would be diffused to some extent and the objection would not be as sweeping as otherwise. There is always "dead water" behind the center pier and abutments of a swing bridge, and there will be "dead" space between the fire-doors and also at the sides. It is not maintained that intermixture of air with all the gases of the fire-box cannot be effected in this manner, in time to accomplish their combustion, but it is a fact that cannot be disputed that such intermixture necessitates a larger surplus of air than will be required when admission is accomplished in some other manner, making possible a greater diffusion of the air. Air entering through the fire-doors comes from one of the lowest strata in the boiler room, and is therefore the coldest air obtainable. All other things being equal, preference should be given to the device that takes its air at the highest initial temperature. The use of the fire-door for air admission makes hand manipulation necessary to regulate the supply, and such manner of regulation is not to be considered when automatic means can be supplied. The movable nature of the fire-door precludes the practical attachment of any automatic mechanism. The low cost, and ease of providing air through the fire-doors, are the greatest arguments in favor of the plan.

SIDE-WALL ADMISSION

Figs. 7, 8, and 9 are referred to in connection with what will be said concerning devices admitting air into the fire-box through the side walls of the furnace. Such furnaces are open to two objections; First, they fail as smoke consumers, owing to the impossibility of mixing the air so introduced with the gases; second, the walls of the furnace and boiler setting are seriously weakened and damaged by the building of air ducts therein, the installation of hollow tile, or other factors necessary to the device.

Consideration of Fig. 7 will make plain the reasons for the first objection. The air entering the fire-box is caught at once

Author's Note: Automatic door closing mechanisms have been used with some success,—the apparatus being arranged to close the furnace door in a predetermined interval of time. While such an arrangement tends to introduce the air in a diminishing volume as suggested by the diagram, Fig. 2, the distribution of the air so introduced is not satisfactory.

by the draft and carried back along the side walls of the boiler and no opportunity is given for intermixture with the gases. The air jets from the side walls enter the fire-box at right angles to the draft of the furnace. No other result than that indicated by the arrows in the drawing referred to can be expected. The gases in the center of the fire-box receive no oxygen, and without that element they cannot be consumed.

The havoc worked to the boiler walls by these side-wall devices will be better understood when the common method of setting a boiler is explained. The "setting" of an ordinary multitubular boiler usually consists of two walls, an exterior and interior. Each wall is about nine inches thick, and the side of the interior wall exposed to the fire is lined with fire-brick. An air space, "C," separates the walls and serves the purpose of insulating the boiler against the escape of heat. The interior walls support the entire weight of the boiler. Now, in order to install tile air ducts, or build air passages in the side walls of the furnace, it is necessary to tear away the brickwork of the wall "B," see Figs. 7 and 9, supporting the forward lugs of the boiler. It is an impossibility to replace these walls in as good condition as they were originally, after such undermining operations have taken place. An examination of the side walls of a boiler employing such a device will in nine cases out of ten develop a crack, running up and to the rear at about the forward face of the bridge wall, as illustrated in Fig. 8. It will be a piece of good luck if the front end of the boiler has not settled to the extent of requiring re-setting. Every engineer understands the dangers arising from scale, etc., when a boiler settles by the forward end.

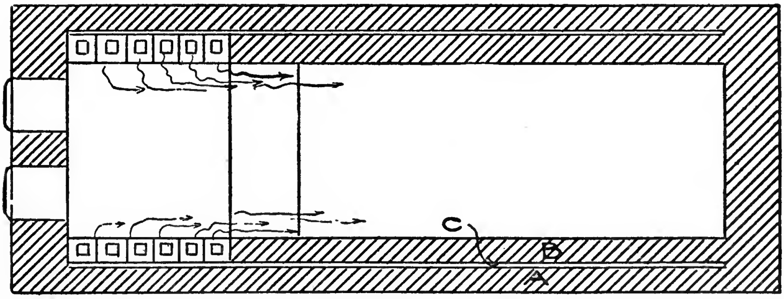


FIG. 7

Even if it were possible to properly rebuild the walls after the installation of such air chambers, the existence of these hollow ducts or passages in what is intended to be a solid wall of masonry, capable of sustaining great weight, would materially weaken it. If the boiler setting is old, or improperly constructed in the first place, the building of such a device practically amounts to the wrecking of the walls. The portion of the walls undermined and weakened must sustain a weight, when the boiler is in operation and full of water to the working line, of from eight to twelve tons. No engineer, alive to the welfare of the plant entrusted to his care, will permit the building of any such device in connection with his boilers. Such contrivances have nothing whatever in their favor. If the boiler is suspended independently of the setting, as it should be, but too infrequently is, the walls of the setting may, of course, be attacked with less danger to the boiler.

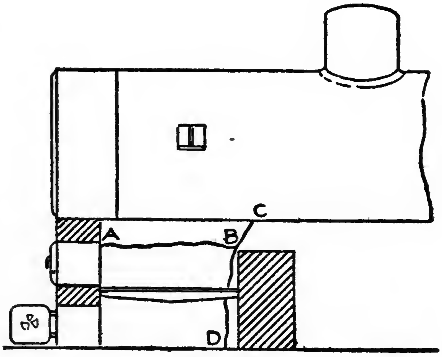


Fig. 8

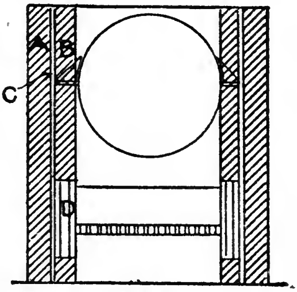


Fig. 9

BRIDGE WALL ADMISSION

The bridge wall has been employed for air admission since time immemorial in the history of smokeless furnaces. There are many things to recommend the use of the bridge for this purpose. There are also valid arguments against it. No damage can be worked to the boiler or setting by any amount of reconstruction of the bridge. The air is heated to some extent upon its passage up through the bridge, and it may be delivered across the entire width of the fire-box. The bridge is also located at the point where the highest temperature exists, and this is in its favor. Let us now look at the objections to the use of the bridge wall and the things to be guarded against if it is employed for air admission.

Unless extraordinary means are employed to heat the air prior to admission, it will enter the fire-box at a temperature below that of the furnace. If colder than the gases, the air will tend to seek the lower strata while the gases will find the upper ones. It accordingly follows as a conclusion, that the air should be introduced above the fire, for in such case the tendencies of the air and gases to find their respective levels will lead to an intermixture. Now, if air is delivered through the bridge wall, it will enter below rather than above the gases, and admixture will take place only to the extent that the air and gas currents come into contact with each other. There will be a current of unoxidized gas, passing over the bridge, next to the boiler, and a sheet of air, cooler than the gases, passing over the bridge, below the gas currents.

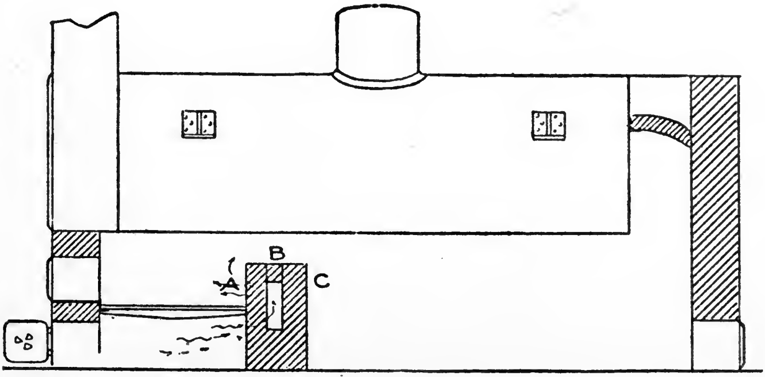


Fig. 10

Fig. 10 illustrates some of the points employed for delivering air from the bridge. There are obstacles in the way of using any one of the points, "A," "B," or "C," or for that matter any other point upon the surface of the bridge, for air delivery. If, for instance, air should be delivered from the face of the bridge wall, as at "A," the discharge openings would soon become fouled with slag, or clinkers, and the device incapacitated for further service. When the bridge wall is low, as is often the case, the fuel will at times accumulate to a height covering the air openings, and slag will attach. If the openings should be at a sufficient height above the grates to preclude contact with the fuel, more or less slag would still attach, as the flames are laden with non-combustible matter, ash, etc., which would adhere upon contact with the brickwork of the bridge. The entire front face of the bridge wall is subject to slag and clinkers, and there is no way to avoid them. If the air openings should be at the top of the bridge, as at "B," there would be a deposit of ashes in addition to the slag, and the openings would not remain very long in commission. When the openings are upon the rear of the bridge, as at "C," delivery of air is too late to meet the requirements of combustion. There will of course be no difficulty at this point from slag, and if the openings are near the top of the bridge, little liability to stoppage from ashes.

In case of air delivery from either side walls or bridge wall, the logical place from which to take the air supply will be the ash-pit. Air taken from this source means robbery of the grates, and this should not be allowed, if avoidable. There will be great difficulty in applying any automatic air-regulating mechanism to air ducts in either side walls or bridge wall.

As between the three methods of air delivery noticed, the advantages lie with the fire-doors.

ARCH ADMISSION

Many devices employ an arch, or arches, for the purpose of air admission. Such arches, if properly placed and constructed, are superior to any of the means already noticed, — the air in such cases being delivered above the fire and the air openings being so located that there is very little if any danger of obstructions by accumulation of slag, or otherwise. There are, however, special objections which apply to the use of arches in certain positions, and these will be considered at the proper time. Air is sometimes delivered to the fire-box from a chamber, built into the brickwork above the fire-doors, and sometimes an air chamber is formed between this brickwork and an arch disposed in front of it, the air being delivered from the chamber into the fire-box in a sheet or in a number of jets. Such constructions have very distinct advantages, but these advantages in themselves are not sufficient to justify claims of superiority, if other necessary factors are absent, while being present in the competing device of another form of construction.

MISCELLANEOUS

Under the head of "Miscellaneous" may be included all those nondescript devices that introduce air at various points in the combustion chamber. Air introduction, posterior to the bridge wall, is too late to be of much assistance in combustion. The gases chill to some extent, in passing from the fire-box to the combustion chamber, and it is better practice to ignite them before they enter the combustion chamber. It is obvious that an intermixture of air must precede ignition. While it is possible to provide such an arrangement of arches and "retorts" in the combustion chamber, as to make combustion of the gases possible after passing the bridge, all such structures are undesirable. There should be no impediments at the rear of the bridge to the easy and frequent removal of ash accumulations. The nearer combustion takes place to the forward end of the boiler, the better, as the hot gases have that much more distance to travel in contact with the heating surfaces of the boiler, and heat absorption will be correspondingly greater.

FIRE ARCH FURNACES

There are so many modifications of fire arch furnaces that it is difficult to make a differentiating classification. They may be classified broadly as, first, furnaces with arches above the grates; second, arches above the bridge wall; third, arches in the combustion chamber.

Furnaces with arches above the grates may be subdivided into those with arches covering the entire grate surface, and those with narrow arches disposed above the grates, usually at a short distance from the bridge wall.

The purposes of these arches, which are variously known as "fire," "retort," "igniting," or "baffle" arches, are to reflect the heat of the fire upon the gases and thus produce a high temperature; to prevent chilling contact of the gases with the boiler shell, and to bring the gases into contact with the incandescent fuel. Some styles of arches also serve the purpose of improving the mixture of the air with the gases. We will first notice the furnace with the arch, covering substantially the entire grate.

In the case of this class of arch, one of the objects aimed at

— the production of a high temperature — is certainly attained. All furnace arches are necessarily constructed of refractory material, usually of firebrick or fire clay tile, which has a large capacity for absorbing and storing heat. This heat is returned upon the fuel bed, and the temperature resulting is excessive, usually far more than is demanded for the combustion of the gases. If air is admitted in sufficient amount, and mixed with the gases, combustion follows as a matter of fact, provided sufficient room exists for the expansion of the gases while in the act of combustion, and provided agencies are not present to check combustion when the burning gases leave the influence of the arch. An arch of the kind under consideration is illustrated in Fig. 11. Unless means are provided to prevent it, the gases will strike the boiler shell immediately upon leaving the arch and experience sufficient chill to cause the precipitation of unoxidized carbon. When fresh coal is thrown upon the rear of the grate, the gases arising will not receive much benefit from the arch and will likely escape unconsumed. Arches at the rear of the bridge wall are often employed in connection with this kind of device, and do much to counteract the tendencies mentioned. Some inventors have gone so far with this type of construction as to extend the arch the entire length of the boiler; some even invert the arch and bolt, or otherwise secure it, to the boiler shell.

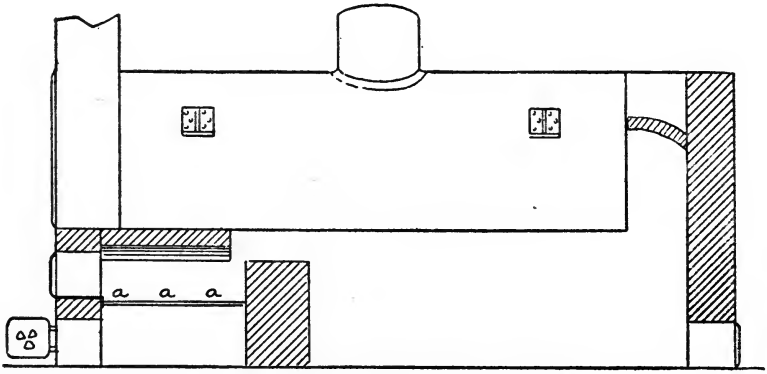


FIG. 11

The objections to this style of arch are numerous and serious. One of the evils to which it is subject comes from the oversurplus of heat. The fireman who can work in front of a furnace so equipped is a sort of a modern Shadrach. Coal contains more or less foreign and non-combustible matter. If the heat of the fire-box is too high, this foreign matter fuses into a clinker before the fixed carbon or coke part of the fuel, which burns slowly, is consumed. A portion of the unconsumed carbon fuses in with the clinker, and is so much fuel lost. The fireman will require no argument as to the undesirability of clinkers, and he has little use for a device that tends to manufacture them. They mean lost fuel, lost efficiency, and extra labor. The non-combustible foreign matter should be left as ash, instead of clinkers, and is left principally in that form when combustion of the fixed carbon is complete. There can be no argument as to economy in favor of burning the gases, if waste of the fixed element of the fuel is to result. Clinkers, moreover, do not tend to improve grate bars, and are in every particular an undesirable quantity. The clinker evil, with a furnace of this kind, is not so marked where a high-grade fuel is burned, but it will exist to some extent if excessive heat is present, no matter what the fuel. If the use of such an arch is attended by an excess of air supply above the fire, the evils as to grates and clinkers are emphasized, as every cubic foot of excess air tends to suppress the movement of a like amount through the grates. If excess heat occurs in the fire-box, considerable energy will be lost by radiation through the boiler front, and the fire-door "liners" and all metal work about the boiler front are liable to suffer, either by fusing or warping, from the excess of heat. The writer has even seen fire-doors warped so badly, where such an arch was employed, that they had to be discarded.

Examination of Fig. 11 will convince the reader that one effect of an arch covering the fire-box is to insulate the heating plates at the forward end of the boiler from the heat of the fire-box. Some heat will, of course, be communicated to the boiler shell through the arch, but the amount will be inconsiderable as compared with what the plates would receive in the absence of such an arch.

Builders of such furnaces will of course claim that there is nothing in this contention, but it may be easily proved by noting the time necessary to raise steam from a cold boiler with such device, and comparing with the time required to get up steam with the ordinary furnace.

The heat stored in such an arch will be sufficient to keep the boiler under steam for an indefinite period after the fire is banked or drawn, making a watch upon the boiler necessary until the arch has cooled. The writer knows of an instance where a boiler equipped with such device showed a gage pressure of 80 lb. on Monday morning, after having been shut down on the Friday evening previous. The safety valve had been popping at intervals in the meantime, and the water, which had been left at a high level, was down at the danger line.

Such an arch of course tends to keep the cold air, rushing in at the fire-doors at the time of stoking or cleaning fires, from contact with the boiler shell until heated to a considerable extent, and this, with many engineers, will constitute quite an argument in its favor. The slow rate at which the boiler may be heated up or cooled off also has some advantages, the welfare of the boiler being in mind.

The fireman will usually object to any arch construction over the fire-box, for the reason, among others, that it offers some obstructions to the use of his fire tools. If the boiler is set low, as many boilers are, such an arch will tend to materially restrict the area of the fire-chamber. With the most careful handling of the fire tools, it will be abraded more or less, and cannot be expected to be a very long-lived structure, particularly if built of brick, and the low point presented by the downward curve of the boiler precludes the use of thick arch blocks. If brickwork is to be interposed between the grates and boiler, the advantage accordingly, with respect to room, appears to lie with the inverted arch, bolted or otherwise attached to, or supported by, the boiler shell. Such construction, however, has its own peculiar disadvantages, which will suggest themselves to any engineer.

Fig. 12 illustrates a very effective form of arch if smoke consumption is the main object in mind. This construction is often referred to as the "McGinnis arch," taking its name from the inventor who first employed it. As the patents have expired, it may be built without fear of infringement, if desired, and with careful stoking may be made to answer the demands of the smoke inspector. The arch shown in Fig. 13 may be employed to some good purpose in connection with this form of construction, but very distinct disadvantages are suffered by its use.

The method of firing employed in conjunction with the "McGinnis arch" is as follows: The fresh coal is fired near the dead plate, and after coking is pushed back against the bridge wall and beneath the arch, and another supply of green fuel placed in position for coking. The volatile gases are drawn away from contact with the boiler shell by the draft, passing down and under the arch. These gases are subjected to high temperature, on passage between the hot arch and the incandescent fuel beneath, and if the correct distances between arch, fuel bed, and bridge wall have been observed and the proper amount of air admitted and mixed with the gases before they arrive at the arch, combustion will be complete, or relatively so.

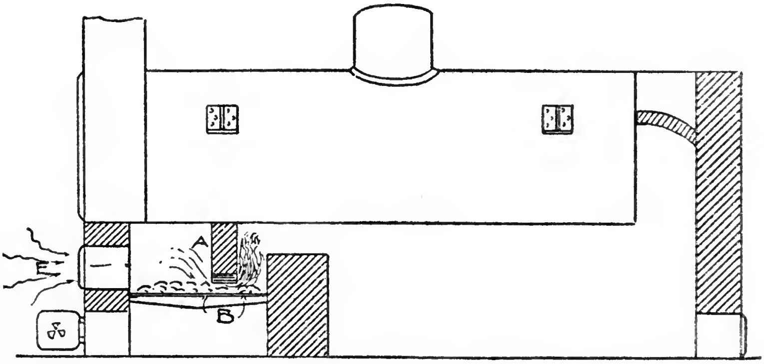


FIG. 12

The objections to the "McGinnis" type of arch are not so numerous as those cited against the construction last discussed. Such objections as do exist, however, are quite marked. There will be little heat thrown out in the face of the fireman and substantially no insulation of the forward part of the boiler shell. There is a distinct limitation as to the methods of firing that may be employed, and it cannot be denied that the "coking" system necessitated imposes some extra labor upon the fireman. The arch is very much in the way of cleaning operations, and considerable clinkering will occur upon the grate, between the line of the forward face of the arch and the bridge wall. The arch will prove a very short-lived structure and require frequent rebuilding, as repairs, owing to the nature of the case are out of the question. Air supply is usually admitted by way of the fire-doors. Objections to this form of admission have already been pointed out.

The most common among the arches employed in the combustion chamber is illustrated in Fig. 13. This arch is usually employed as accessory to some other form of construction, and is here discussed, for the reason that it was a constituent part of the original "McGinnis furnace." The office of the arch is to divert the gases from the cold shell of the boiler. The deflection of the gas currents also serves to complete the mixture of the air with the gases, if such admixture has not fully taken place before the arch is reached. Any arrangement that will secure complete mixture before the bridge wall is passed is of course preferable. Ignition should occur at or near the bridge, as the gases then have the use of the entire combustion chamber in which to expand and give up their heat to the boiler.

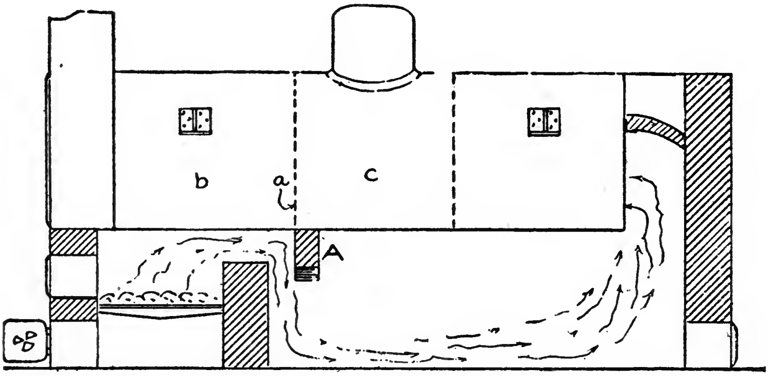


Fig. 13

An extremely bad effect of the "baffle" arch is illustrated in Fig. 13. The course of the gases after contact with the arch is about as shown in the illustration, and a marked loss of efficiency is the result. It is desired to apply the heat of the gases to the plates of the boiler and not to the floor of the combustion chamber. It has been estimated by careful engineers that such an arch will impair efficiency to the extent of at least 10 per cent. An observing experience with it will lead any one to about this conclusion. That the course of the gas currents is substantially as shown in Fig. 13 may be settled by a look into the combustion chamber when the furnace is in operation. A sight hole for this purpose may be drilled in the door to the combustion chamber, at the rear of the boiler. To avoid the diversion of the gases from the heating plates of the boiler, the arch is sometimes provided with apertures or "checker-board work," through which the gases stream along lines parallel to the boiler. Such arrangement tends to neutralize the work of the arch, as combustion, it has been demonstrated, is promoted by concentration of the gas currents, and any tendency to break up these currents leads to the opposite effect. Such apertures are disposed to become clogged with ashes in a short time, when the gas currents will to a great extent take the direction shown in the illustration.

It can be readily understood that the heat immediately in front of such an arch is far greater than at the rear. The arch, as it is usually placed, is about flush on its forward face with the boiler seam, "a," Fig. 13. The arrangement of the heating plates of the boiler may be such that no seam occurs in this neighborhood, but such seam will usually be found in about the locality indicated. When the boiler plate, "b," is subjected to a high degree of heat and a relative expansion, and the plate, "c," to lower heat and less expansion, but one thing can happen to the seam and rivets at "a." They will be subjected to terrific strain, and if leaks are not started in a short time it will not be the fault of the arch. If found necessary to use the arch illustrated in Fig. 13, it would be well to construct a secondary bridge wall at the rear of the arch to redivert the gas currents and bring them into contact again with the boiler plates.

The purposes performed by the arches illustrated in Figs. 11 and 12 are accomplished by those devices which employ an arch over the bridge wall, and an arch in this position is not subject to the objections cited against the other constructions. The heat reflected and radiated from such arch will be directed against the bridge wall where no harm can result. The grates will not suffer and there will be no tendency to clinkers. If the arch and bridge are properly constructed with reference to each other and to the draft, and air is supplied in the proper manner, there will be no question as to the combustion of the gases, as ample temperature will exist in the passage between the arch and bridge.

The following difficulties arise in connection with all arches, no matter where located under the boiler, although these difficulties are more pronounced with arches located over the fire-box, as they are subjected to a higher degree of heat.

When the arch becomes heated, it necessarily expands and exerts a tremendous pressure upon the side walls of the boiler setting, at and above the points where the "skewbacks" of the arch are located. This pressure may be sufficient to displace the walls from contact with the boiler. The writer has seen such results due to an arch.

Nearly all forms of furnace arches are short-lived. This is largely due to the contraction and expansion to which the arches are subject, in connection with the displacement of the walls against which the "skewbacks" are placed. A very slight movement upon the part of the walls supporting the arch will be sufficient to bring the arch down, when cooling and contraction occurs, as the walls will not spring back into position to take up the contraction of the arch. It is advisable to employ some form of reinforcement against the lateral thrust of the arch.

From the foregoing, it will appear that the subject of furnace arches is one that involves many considerations, and that the arches in most common use are open to many and often vital objections. The igniting or deflecting arch, above or forward of the bridge, may be regarded as a necessity, however, where the best results as to smokelessness are desired. The purchaser must exercise his judgment in the selection of a device, and choose that one which is best adapted to his boiler and presents the least number of objectionable features. As a general proposition, that arch which presents the least surface above the grates and which is least in the way of the operations of the fireman, is the one to select.

A modification of the arch above the bridge wall is sometimes found in a "checker-board" construction, extending in some instances from the grates to the boiler. There is nothing to recommend such an arrangement. The same argument applies that has been advanced against the perforated baffle arch. There is tendency, also, to bottle up too much heat in the fire-box.

DUTCH OVEN FURNACES

The "Dutch oven" furnace is illustrated in Fig. 14. This device, which is in more or less common use, consists of a furnace located outside and usually in front of the boiler setting. It is of course necessary to provide the furnace with a roof of refractory material. Firebrick arch blocks are usually employed. The objections that have been pointed out against the use of an arch over the fire-box apply with equal weight to the "Dutch oven." It is always a clinker maker and gives the fireman a foretaste of the inferno. It requires extra room, and its construction involves considerable expense. There is also liability of considerable loss from the radiation of heat. This may be reduced to the minimum by proper construction and installation. A "Dutch oven" should not be employed if any other device will answer the purpose. There are cases, however, where it is the only expedient, and one that it will be advisable to employ, notwithstanding the objections that go with it. In the case, for instance, of such a boiler as is illustrated in Fig. 3, a furnace of this type is about the only effective resource available, if hand firing is to be employed. The same is to a great extent true of the internally fired boiler, — notably the marine boiler. Coking chambers are sometimes employed in conjunction with a "Dutch oven" furnace. These will be treated under the head of "Down-Draft Furnaces."

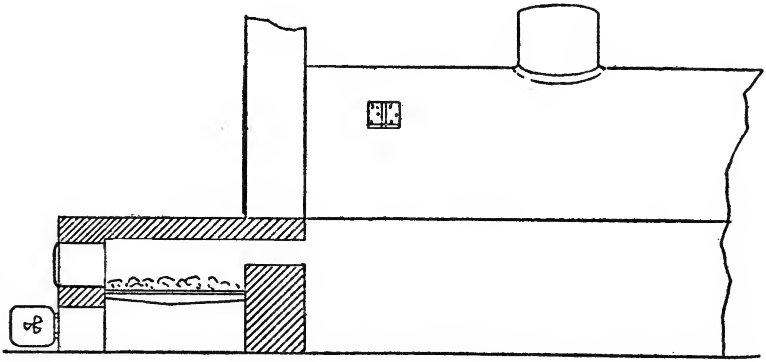


FIG. 14

DOWN-DRAFT FURNACES

The "down-draft" furnace is by no means a modern engineering invention. Both Watt and Franklin designed forms of furnaces employing the "down-draft" principle, and their ideas have not been greatly improved upon, except in details of construction. Fig. 15 illustrates in a general way the most common type of this style of device now on the market.

Two grates are usually employed in the "down-draft" furnace, as shown in the illustration. Coal is fired upon the upper grate, which is composed of widely separated bars or water tubes. The draft enters through the open fire-door and passes down through, first, the green, freshly fired coal, and then the ignited portion. The theory is that the gases distilled from the green coal are mixed with air, and ignited and burned while being passed through the underlying incandescent fuel. After the coal is coked, it is expected to drop through the grates upon the second grate, which may be composed of ordinary straight bars and set up in the usual manner. The combustion of the coke or fixed carbon is completed upon this second grate. It can be seen that such a furnace has somewhat narrow limitations with respect to coal. If, for instance, the coal is too fine, it will fall through upon the second grate before coking is completed, and there will be smoke. If the coal is too coarse, it will not pass through the upper grate after coking is completed, and the fireman will be compelled to rub it through with a fire tool. If this is done at a time when uncoked coal is upon the upper grate, some of it will probably accompany the coke to the lower grate, and there will be smoke. If it is desired at any time to force the furnace to meet an extra demand for steam, coal must either be thrown direct upon the lower grate, or the uncoked fuel upon

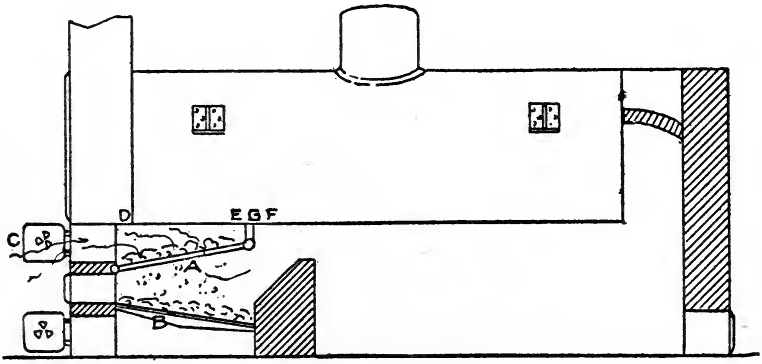


Fig. 15

the "coking grate" must be forced through upon the lower grate in order to make room for a fresh supply of green coal. In either case there will be smoke. To force such a furnace without producing smoke is an exceedingly delicate operation.

It will be seen upon reference to the drawing, that cold air is at all times in contact with the boiler shell, between the points "D" and "E." The strain upon the plates at "G" must be considerable, owing to the wide difference in temperature between the points "E" and "F." There must also be considerable loss, owing to the cooling influence of the air upon the exposed boiler shell, between "D" and "E."

If an even load is carried and the demands upon the boiler are not excessive, such a device with careful firing will give good results as to smokelessness. Otherwise there will be constant trouble. With the "down-draft" furnace, as with most other devices, a great deal depends upon the assistance of the fireman. The cost of this device, as compared with many others, showing equally good combustion, is excessive.

A number of furnaces employ a coking chamber at the sides or front of the fire-box. The fresh coal is placed in the chamber, which is left open to the air, the down-draft principle being utilized. The coal settles gradually as coking proceeds, and fresh fuel is supplied when required to keep the contents of the coking chamber at the proper level. The fireman must occasionally insert a slice bar or other tool, and distribute the coked coal over the grates. A "Dutch oven" is usually employed in conjunction with such device, but some are to be found with coking chambers under the boiler in the angle formed by side walls and boiler shell. The expense of any of these contrivances is necessarily considerable, and very careful handling is required. If the boiler is subject to a fluctuating load, difficulty will be experienced in persuading the furnace to respond readily to the changing conditions.

CHAPTER VIII

SOME CONCLUSIONS

The aim of the author has been to carefully point out the undesirable features of every type of "Smokeless Furnace" likely to be offered to the coal consumer. Some of the devices on the market combine the features of several types, and these features must be weighed separately and in combination. It is indeed a poor device that has no good features, and it is certainly a good device if it possesses no failings. The man who is looking for absolute perfection in this field will be disappointed, for nothing in the furnace line can be endowed with the factor of intelligence, and even if so endowed it would often have a hard proposition to contend with, in the ignorance and carelessness of the men in charge of the boiler. In selecting a device, the purchaser should be guided by his judgment and place very little reliance upon the statements and claims made by the "smokeless furnace" salesman. He must have sufficient general knowledge of the requirements of combustion, and he must take into account the conditions obtaining in his own plant. The fact that a device is giving good satisfaction in his neighbor's plant cannot be taken as evidence that it will give equally good satisfaction in his own. What is well adapted to one set of conditions and circumstances, may not be at all adapted to another. It may be well to cite, by way of recapitulation, the conclusions to be drawn from the author's arguments.

The conditions necessary to the combustion of the gases given off in the fire-box are as follows:

1st. The introduction into the fire-box, and the commingling with the gases, of a sufficient amount of free oxygen to effect the oxidization of the combustible elements.

2d. The maintenance of the combustible gases at the requisite temperature, until combustion has been completed.

3d. Sufficient room for the expansion of the gases while in the act of combustion.

If the above conditions are present, combustion will be complete, but it must be borne in mind that complete combustion does not necessarily mean increase in efficiency. It may be, and in the case of most smokeless furnaces is, accomplished at the expense of efficiency, owing to the introduction of a redundant supply of air. If fuel economy is desired the following must be provided for:

1st. Regulation of the air supplied to the fire-box to meet the changing requirements of the gases; such regulation, to be practical, must be accomplished automatically.

2d. The device must be adjustable by experiment to meet any combination of conditions offered by the boiler, grates, draft, etc., and must be capable of easy and quick readjustment, to meet any change of conditions brought about by the use of a different grade of coal, different method of firing, etc.

That device is of course to be preferred which both meets the conditions necessary to complete combustion and is equipped with means to secure such combustion with the greatest economy.

The mere fact that a furnace is equipped with means to automatically and adjustably regulate the air supply, is not in itself sufficient to guarantee that combustion of the gases will take place with the greatest economy. The temperature of the air introduced, and the manner of its admission to the fire-box, are factors of importance. The hotter the air, the less heat it will abstract from the burning gases, the more immediate and intimate will be the mixture of air and gases, and the less weight of air will be required. If the air is diffused in a thin sheet, or in a large number of jets, across the entire width of the fire-box and above the fire, there will be better opportunity for admixture with the gases, and less air will be required to accomplish combustion than if admission is given in some other way. All other things being equal, that device is best which introduces the air at the highest temperature and in such manner that it will most freely mingle with the gases to be burned.

Initial cost and expense of maintenance are items to be considered. Other matters being equal, these factors should enable the purchaser to decide between competing devices. They are not, however, of primary importance, as a cheap device may prove the most expensive in the end.

Damage may result to boiler and setting by the installation of the factors necessary to a "smokeless furnace." We will briefly review the dangers to be guarded against, most of which have already been pointed out. The purchaser should carefully inquire into the construction of a device before contracting for it, and make sure that no serious menace is offered either to his boiler or setting. Following is a partial list of what may result to the boiler and setting by the installation of various devices:

Damage to the boiler may result by

1st. Tapping the shell to connect water tubes, attach tile or other elements in connection with the device. Fire tubes are sometimes removed and pipe connections made at the openings. It is bad practice to interfere with the integrity of the boiler in any manner.

2d. "Bagging" of boiler shell may be caused by concentration of too much heat at one point, or the accumulation of too much sediment at the forward end of the boiler. Incorrect arrangement of arches may lead to this result, and weakening of the side walls may cause settling at the forward end of the boiler and deposit of scale over the fire-box.

3d. Leaking at the seams, due to unequal heating of the boiler plates. Causes have been pointed out.

4th. Formation of scale on exterior of boiler shell and tubes, due to precipitation of carbon by "steam jets."

5th. Pitting of boiler shell and tubes, caused by sulphur compounds in the scale deposited by "steam jets."

Damage to boiler setting may result by

1st. Undermining the walls of the fire-box, in order to install hollow tile or build air conduits or chambers.

2d. Spreading of walls by the lateral thrust of non-self-supporting arches.

Damage to grates may result by

1st. Use of "steam jets," the steam blown into the fire-box or elsewhere, posterior to the grates, displacing an equal volume of air and retarding, to that extent, the draft through the grates.

2d. Introduction of surplus air above the fire, such surplus air retarding the grates in the same manner as the "steam jet."

3d. Drawing air supply for fire-box from ash-pit.

4th. Oversurplus of heat in fire-box, caused by superimposed arches and resulting in clinkers upon the grates.

Damage to metal work at front of boiler, may result by oversurplus of heat in fire-box.

Damage to efficiency may result by

1st. Over-surplus of air supplied to gases.
2d. Diversion of gas currents from boiler shell, as in the case of "retort" arch at rear of bridge.
3d. Insulation of boiler shell from heat of furnace, by arch disposed over fire-box.
4th. Exposure of part of the heating surface of boiler to draft of cold air, as in case of device illustrated in Fig. 15.

All other things being equal, that device should be given preference that has no limitations as to quality of coal or methods of firing, and which imposes no extra duties or hardships upon the fireman.

There are other objectionable features of minor importance, peculiar to some furnaces, but space precludes mention of them. They are usually so obvious as to be apparent on examination of the structural features of the device.

If a mechanical stoker is to be employed, the purchaser must select the one best adapted to the circumstances of his case. Preference might be determined by the facilities provided for regulating the feed of fuel and the free air supplied to the burning gases. Other things being equal, that stoker is the best which requires the least care to secure efficient operation, and which has the fewest limitations with respect to character of coal.

With induced draft a vacuum is maintained in the furnace and the passes of the boiler and this invites the entrance of outside air through every crack and crevice in the setting where it can gain admission. With forced draft little or no vacuum is necessary.

THE "TEST" DELUSION

If the author can succeed in discrediting the "evaporation test," as an evidence of furnace efficiency, he feels that he will have accomplished a service to engineering. Such tests may be made to prove anything desired; place no confidence in them. The above stricture is not intended to apply to the evaporation test as an evidence of boiler efficiency.

"Smokeless furnace" literature is full of the reports of evaporation tests, purporting to show and prove increased efficiency. Every life insurance company claims superiority over every other, and proves its claims by an imposing array of statistics and figures. There are more opportunities for "juggling," in making an evaporation test, than any insurance actuary has ever been able to discover in his business. Properly and honestly made, the evaporation test is indicative of something as to furnace efficiency, but the best of such tests is not conclusive. If not properly made, the evaporative test is indicative of nothing. So many contingencies enter into the situation, that it is even possible for a competent and experienced man to fool himself in making such a test. If such test must be made, and reliance is to be placed in it, it should extend over sufficient period to insure an averaging of conditions, and should be conducted by parties in whom those interested in the test have the utmost confidence.

No less than one hundred items, each one of importance, must be considered in running an evaporation test properly. If one of these items is not taken into account, the data is incomplete. Take, for instance, the matter of atmospheric conditions. The pressure of the atmosphere, as registered by the barometer, has a bearing on the draft of the chimney. The temperature of the air applied to the fire affects the temperature of combustion, and this has a direct bearing upon evaporation. The degree of moisture in the atmosphere also affects the temperature of combustion. The coal used must be carefully analyzed, and every wheelbarrow of fuel delivered to the fireman sampled for this purpose. The resulting ash and clinkers must be weighed and analyzed before we are able to say what amount of combustible has actually been used. We must know the percentage of moisture entrained in the steam; and, if such test is to be absolutely accurate, we must know a number of things that are not ascertainable, and consequently never taken into account in conducting a test. For instance, the amount of heat stored in the walls of the boiler setting may be sufficient to account for several hundred pounds of coal, enough in a test run of ten hours to have a bearing of several per cent. upon efficiency. If tests are being conducted to determine the efficiency of a special furnace, and such test is in charge of a representative of the device, as is usually the case, advantage will probably be taken of everything tending to give the furnace the least advantage. If the man who is conducting the test knows his business, the result will show a gain in favor of the device, when, as a matter of fact, an actual loss might be experienced. It is to the interest of the device, that the test made before its installation be conducted under as unfavorable circumstances as possible. No effort will be made to clean the boiler shell, or stop air leaks, and no special care will be taken in firing. When the device is installed, there will be a general house cleaning about the boiler. Scale will be rubbed off the shell, and every square foot of heating surface made as clean as possible. It will also help some to clean the stack and breeching, if dirty. All air leaks will be stopped, and everything possible done to put the furnace and boiler in the pink of condition for a record performance. The test will be started with the setting as hot as possible, and great care will be exercised in firing. Such precautions alone are good for a showing of from ten to twenty per cent. improvement in efficiency. Those best acquainted with the evaporation test place the least confidence in it.

The proper test to apply to any device claiming to improve combustion is a flue gas analysis. Such analysis not only determines the extent of the combustion but the percentage of surplus air carried with the chimney gases. If combustion is at the maximum, and surplus air at the minimum, the highest efficiency possible is attained. The amount of water evaporated per pound of coal, the quality of the steam and every other item that must be noted in connection with an evaporation test, may be disregarded. The evaporation test is necessary to determine boiler efficiency, but should not be employed to determine anything related to combustion.

APPENDIX.

This volume would be incomplete without an appendix describing the combustion testing apparatus most commonly employed in working out smoke problems and improving the efficiency of furnace and boiler. The author ventures to illustrate certain apparatus designed by himself and in doing this he must not be considered as disparaging any apparatus that may have been designed by others. Something should also be said about soot, because soot deposits constitute one of the most expensive results of incomplete combustion.

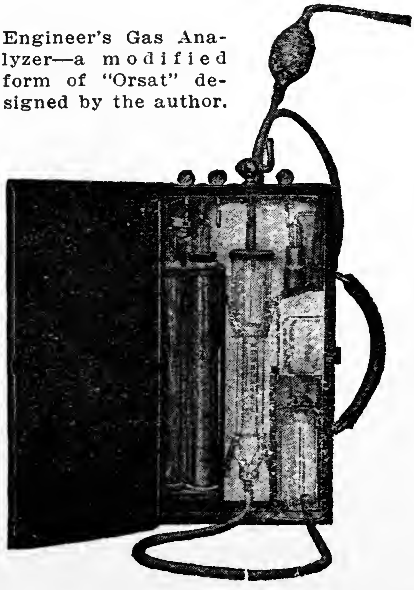
As pointed out in the preceding pages smokeless combustion depends upon proper furnace design and proper fuel and air supply. If there is lack of air, lack of temperature, lack of mixture between the air and the gases or lack of space, there will be smoke. The smoke from your furnaces may be due to one of these causes. It may result from a combination of two or more of them. You cannot provide a proper remedy for the smoke until you know absolutely what the causes of the smoke may be. You may waste a great deal of money if you buy smokeless furnaces and automatic stokers on the representations of the salesmen alone. Most of these salesmen can point to satisfactory results that have been attained in other plants. But you must remember that the other plants are not your plants and that a remedy exactly adapted to the smoke trouble in one boiler room may fail absolutely to meet the situation in another. Your particular case must be "diagnosed" before the contract is placed for the furnace or stoker.

And you must remember, as the author has been at pains to point out, that a smokeless furnace is not necessarily an economical furnace. In this connection the reader may again refer to the discussion relating to the diagram, Figure 2, preceding.

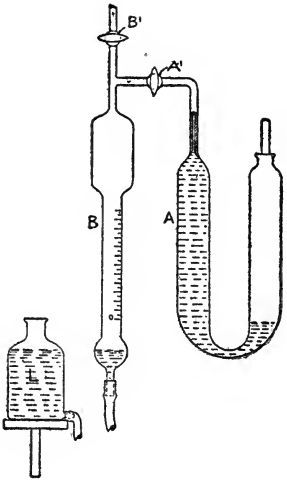
It is easy to determine whether there is sufficient temperature for combustion. Mere observation of the fire will be sufficient. If the furnace is white hot, the smoke is not due to lack of temperature. It is not so easy to determine which of the other three causes mentioned may be responsible for the smoke. If the furnace dimensions are known, together with the areas of the various boiler passes, etc., we may make a fair guess regarding the matter of space, but it would be a guess, and guesses are often wrong. The space required depends upon the flaming characteristics of the coal. What would be ample space for one fuel might be very inadequate for another. We may proceed with certainty in diagnosing combustion problems, only when we are equipped with proper combustion testing apparatus.

ILLUSTRATION SHOWING THE "ORSAT" PRINCIPLE OF GAS ANALYSIS.

The gas to be analyzed is taken into the "burette" "B," the cock "B1" being opened for the purpose. The "Leveling Bottle" "L" is filled with water. "L" is then raised with the hand and water flows from it through the connecting rubber tube into "B," "seeking its level." "B1" is closed when the water reaches the zero mark on the scale etched on "B." The water levels in "B" and "L" should then be in the same horizontal plane, thus giving a measurement at atmospheric pressure of the exact gas sample called for by the "burette."



Engineer's Gas Analyzer—a modified form of "Orsat" designed by the author.



"A" is charged with a gas absorbing liquid. The cock "A1" is opened and "L" raised, the water driving the gas from "B" into "A," displacing the liquid in the latter. The CO_2 contained in the gas is absorbed by the liquid and this causes a contraction in the gas sample. The gas remaining is then pulled back into "B" by lowering the Leveling Bottle. The chemical (Caustic Potash solution) must be drawn up into the capillary tube at the top of "A" before the cock "A1" is closed.

The bottle "L" is then held in such position that the surface of the water is in the same horizontal plane as that of the water in "B." This places the gas under atmospheric pressure and the reading is taken.

Additional absorber pipettes, similar to "A," are connected by a manifold with "B" and charged with the proper solutions if Oxygen and CO are to be determined.

THE GAS ANALYZER APPLIED TO SMOKE PROBLEMS.

It may be quickly determined with the Gas Analyzer whether the air supply is sufficient or insufficient. If the escaping furnace gases contain 5 or 6 per cent free Oxygen, there is ample air for complete combustion and the smoke must be charged to one or more of the three remaining causes. The question of temperature, as already stated, may be settled by observation of the fire in the furnace, and if the temperature required is actually present we will know that the smoke is caused by lack of mixture or lack of space.

If, on further examination of the gases of combustion, CO (Carbon Monoxide) is present, a strong presumption arises that the smoke is due to lack of mixture, because free Oxygen and combustible gas cannot exist together in the presence of an igniting temperature. If, however, the Carbon Monoxide is produced in one part of the furnace and the excess, or unused oxygen, rises through the grate into another portion of the furnace, the two may not come into contact until the furnace and the various passes of the boiler have been traversed, when the temperature may be too low to promote ignition.

A better mixture can usually be promoted by more skillful firing. The fuel upon the grate should at all times be kept in such condition that there will be a uniform distribution of air through the fuel bed. Such distribution is possible, only when the fuel bed is of uniform resistance, viz., of uniform thickness, free from holes and fissures and the grate free everywhere from ash accumulations. If the fuel bed is thick in some places and thin in others, and especially if the grates are bare in places or if there are holes or fissures in the "fire" the air distribution will be very uneven. Where the fuel is excessively thick, CO will be formed.

If satisfactory mixture cannot be secured by equalizing the air distribution through an improved firing practice, the engineer of the plant may be forced to resort to some of the expedients described in the body of this book, viz., mixing or baffling arches, piers, etc.

There may be dense black smoke in the absence of combustible Carbon Monoxide, in which case it is reasonably safe to conclude that the prime cause is lack of space. When the burning gases come into contact with the cold heating surfaces of the boiler, carbon is precipitated as soot. When smoke is caused in this manner, it may be very black and dense and there may be no trace of Carbon Monoxide present. If smoke is caused by lack of mixture, some measure of Carbon Monoxide is almost certain to be found in the gases.

The author has tried to show that a clean chimney does not necessarily indicate efficient combustion, for it is indisputable that combustion may be complete at furnace temperatures much lower than those called for by good practice,—the lowered temperatures being caused by the introduction of a large excess of air through the fuel bed.

More fuel waste is caused by excess air than by all other agencies combined and a redundant supply of air usually contributes to the completeness of combustion by improving mixture. Hence it is possible for a steam plant to experience a decrease in smoke with an attendant decrease in efficiency. These things are not generally understood. Smokeless combustion is not necessarily economical combustion.

All combustion problems, however obscure or complicated they may be, are quickly cleared up by means of the Gas Analyzer. In ordinary boiler furnace practice it is not often necessary to go further than the determination of CO_2. Knowing the percentage of Carbon Dioxide, we know approximately the percentage of free Oxygen (excess air) in the flue gases. The following formula may be used in computing the air excess from the CO_2:

$$\frac{20.7 - CO_2 \text{ percentage}}{CO_2 \text{ percentage}} \times 100 = \text{Excess air.}$$

In the following table the air excess corresponding to percentages of CO_2 from 1 to 20.7, inclusive, is shown:

Per cent CO_2.	Per cent Air Excess.
1	1,970
2	935
3	590
4	417
5	314
6	245
7	195.7
8	158.7
9	130
10	107
11	88.1
12	72.5
13	59.2
14	47.8
15	38
16	29.4
17	21.79
18	15
19	8.95
20	0.035
20.7	0.000

At about 1.5 per cent CO_2, the cooling effect of the excess air in the furnace gases is so great that the efficiency of the furnace and boiler as steam generators would be zero.

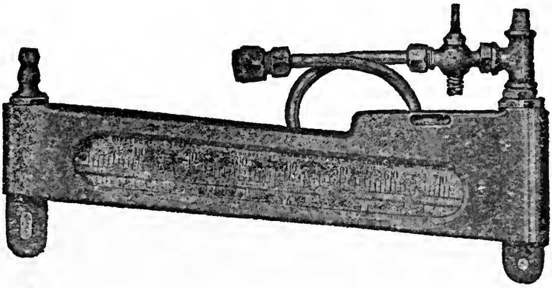
Boiler plants that are operated without combustion supervision show upon the average about 6 per cent CO_2, while it would be easy in nearly every case by a little attention to the air leaks common in brick boiler settings and a little study of drafts and methods of firing to increase the percentage to 14 or 15, thereby reducing the air excess from about 245 to around 40. This would mean a reduction in fuel consumption of about 17 per cent.

Draft is an extremely vital factor in furnace efficiency. There is some draft that will produce the best results and the engineer in charge of the plant must ascertain what his standard draft for normal working conditions may be. Having learned this he must see that such draft is applied to all of his furnaces all of the time, as far as may be practicable. Change in load may require change in draft, but the standard working draft should be adhered to as much as possible.

A differential draft gage properly connected at the furnace is of great assistance to the fireman in maintaining efficiency. If there really is, as already stated, some draft that will produce the best economy in the consumption of coal, the fireman cannot be held to the use of that draft unless he is provided with gages showing the draft. He must be instructed what draft to use. Each boiler is provided with a water gage in order that the fireman may know at all times the stage of the water in the boiler. A draft gage for each boiler furnace is necessary in order that the fireman may know at all times the state of the draft in the boiler furnace. And as the fireman is taught to vary the water level in the boiler within certain limits in order that the boiler may accommodate itself to fluctuations in the load, he may also be taught to vary the drafts within certain limits that the furnace may easily respond to like fluctuations in load.

The fireman soon learns to employ the draft gage as an indicator of conditions inside the furnace. A decreasing draft indicates that holes are forming in the fuel bed or that the fuel is being reduced in thickness and an increasing draft shows that the fuel bed is too thick or that the fires are getting "dirty."

Air leaks are the most common causes of draft interference. These may occur at any place between the furnace and the top of the chimney. The function of the chimney is to create a partial vacuum inside the furnace, and as a result of the difference in pressures, air flows into the furnace through the fuel and the necessary oxygen is supplied to the combustible. Any opening between the furnace and the top of the chimney will admit air, thereby "breaking" the vacuum and impairing the draft. Serious air leaks are common at the places where the breeching connects with the chimney and with the boiler. These leaks impair draft, but they do not necessarily impair combustion efficiency. Air leaks are extremely common about boiler settings—especially about the settings of water tube boilers. Such leaks admit air to the heating surfaces of the boiler and impair both draft and efficiency.



Type of Differential Draft Gage designed by the Author.

There is but one rule of general application regarding draft, and the term "draft" as here used must be understood to mean the vacuum in the furnace over the fire.—"That draft which will produce the highest percentage of CO_2, without CO, and which will carry the load, will produce the highest economy in fuel consumption."

The above being true, it is necessary to know something about the constitution of the flue gases before fixing upon the

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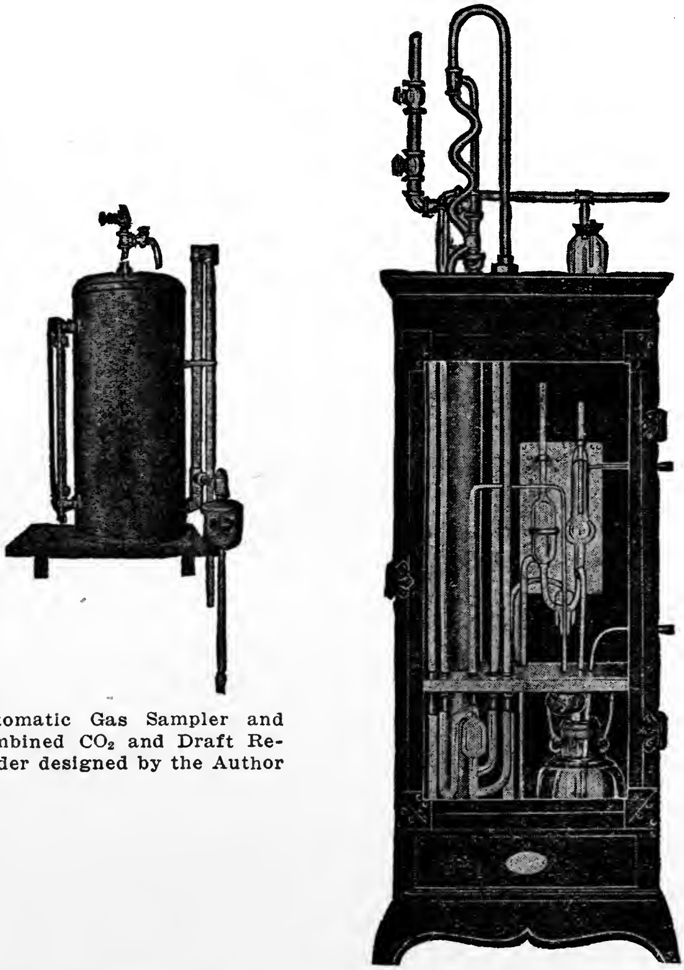
*For a discussion of efficient combustion, see "How to Build Up Furnace Efficiency," by the Author.

standard draft for the plant. When the standard draft is known it remains to apply this draft to all furnaces by adjusting the individual boiler dampers and to maintain this draft at all times so far as the fluctuations in the load will permit. All authorities seem agreed upon the proposition that the Gas Analyzer provides the only certain means of determining the draft to be used.



Automatic Gas Sampler and Combined CO_2 and Draft Recorder designed by the Author

Let us assume that the draft selected as the standard for the plant is thirty-hundredths of an inch over the fire and that the use of such draft together with skillful firing will produce an average of 14 per cent CO_2 in the chimney gases. It remains to make certain whether the firemen are employing the proper draft and observing all the instructions that may have been given them regarding firing or the operation of the stokers. To this end an automatic CO_2 Recorder or an Automatic Gas Collector may be employed. The Recorder produces records upon a chart at intervals of a minute or more as desired, showing the percentages of CO_2 in the flue gases. The Gas Collector traps a quantity of the flue gases drawn at a uniform rate over any desired period, as for example a firing watch, and at the end of the period the trapped gas is analyzed and the percentages of CO_2, Oxygen and CO are determined. The illustrations show the CO_2 Recorder and the Gas Collector designed by the author.

The subject of combustion cannot be dismissed without a consideration of soot. Soot is inevitable wherever a carbonaceous fuel is burned and practically all fuels are based on carbon. The better the combustion the less soot there will be. But no matter how ideal the combustion conditions may be, soot will be formed at certain stages, as for example when fresh fires are being started, and it requires but a thin coating of soot upon the heating surfaces of the boiler to seriously retard the transfer of heat to the water. A pound of carbon reduced to the form of soot and distributed upon the heating surfaces of a boiler will interfere in a very marked degree with the efficiency of the boiler as a heat absorber.

The non-conducting properties of carbon, and especially of carbon in the form of soot, are not generally understood. An idea of the relative conducting properties of steel and carbon may be obtained by taking a charcoal pencil in one hand and a steel bolt in the other and then holding the ends of the two in the flame of a Bunsen burner. The bolt will be too hot to hold in a few moments, while the charcoal pencil may be held indefinitely.

It has been determined that one square foot of steam pipe at a temperature of 310 deg. F. will transmit heat units through various coverings one inch thick as follows:

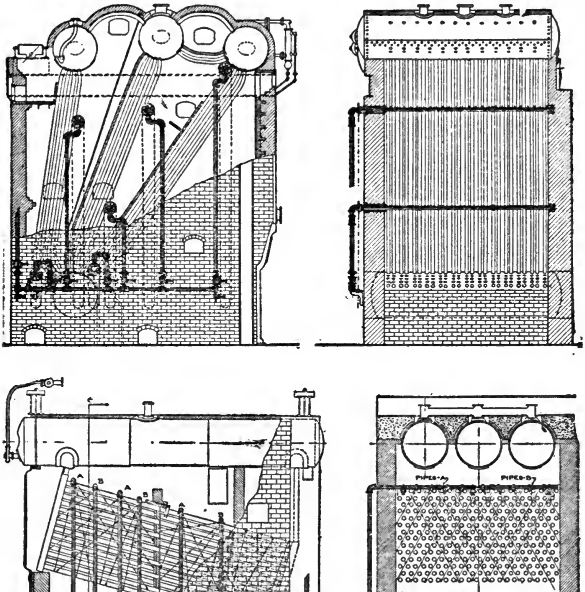
Covering.	B. t. u. per sq. ft. per minute.
Fine Asbestos	8.17
Loose Anthracite Coal Ashes	4.50
Asbestos Paper (wound tight)	3.62
Cork Strips (bound on)	2.43
Paper	2.33
White Pine Charcoal	2.32
Cork Charcoal	1.98
Compressed Lampblack	1.77
Loose Lampblack (soot)	1.63

From this table it appears that soot will resist the transference of heat five times as effectively as fine asbestos and we are struck by the fact that a coating of soot one-tenth of an inch thick on the boiler surfaces will interfere as seriously with that boiler as a coating of fine asbestos one-half inch thick. It will also be observed from the table given, that loose anthracite coal ashes make an insulating covering almost twice as effective as asbestos. Incidentally the table shows why cork as an insulating material is coming so rapidly to the front in popular favor.

Deposits of soot upon the boiler to some extent are inevitable, no matter what the fuel. They will even occur where gas is burned. Deposits of ash, especially where high ash bituminous coals and steam grades of anthracite are burned, may be quite as troublesome as soot. Good practice demands the employment of proper equipment to keep the boilers clean of soot and ash accumulations.

Soot is always an evidence of improper combustion and there is always a time when the best designed furnace will suffer from improper combustion and produce some smoke and some soot. Again the best designed furnace may deposit ash all of the time. Hence it is quite imperative when designing a boiler plant to make proper provision for the frequent and thorough cleaning of the tubes and other heating surfaces.

The author is disposed to question the thoroughness of what have come to be known as "hand blowers," because it is quite impossible to bring such blowers to bear upon all of the heating surfaces and impossible again to so direct the steam jets from a hand blower that the soot will be effectively driven away from the parts actually "cleaned." The illustrations show approved and very effective permanent soot blowers as arranged for Stirling and B. and W. types of boilers. With such an installation it is possible to effectively sweep every square inch of the heating surfaces and to blow the passes of the boiler progressively, thereby forcing all of the soot from the boiler to the chimney.



Showing Permanent Installation of Soot Cleaners on Stirling and B. & W. Type of Boiler.

The author will leave the question of soot removal by quoting from an article in the March 10, 1914, issue of "Power" written by Chas. Bromley, one of the editors of that magazine.

"An engineer with an eye for economy looks carefully after his boiler setting so as to reduce the air leakage to a minimum. The practice of encasing the whole setting in steel is excellent and is increasing, but engineers realize that there is a greater gain if the blow doors are also encased, as it is practically impossible to keep these doors air-tight. To overcome this difficulty, it has become common practice to omit the dusting doors and steel case the entire setting, and install some type of mechanical soot blower for cleaning the boiler tubes.

One of the largest New York companies recently installed thirty-two 600-horsepower horizontal water-tube boilers, 14 tubes high by 21 tubes wide. These boilers are steel cased with no provision for hand cleaning. The boilers are cleaned by means of a mechanical soot-blowing system, consisting of eight 2-inch blow pipes, which extend across the width of the boilers. Four of these pipes are at the top of the first pass, two at the top of the second pass and two at the top of the third pass. Each pipe is equipped with special three-way nozzles drilled so as to project the steam obliquely between the tubes. The nozzles on alternate blow pipes project the steam down through the space between the tubes on intersecting planes and between different pairs of tubes, so that the steam cross-fires over the heating surface. An additional 2-inch pipe with smaller branch blow pipes cleans the superheater.

In the article under discussion the statement is made that the worst feature of all forms of fixed-jet apparatus is that they cannot be spaced close enough to effectively clean the tubes. This statement seems hardly in keeping with the evidence at hand. The foregoing tests indicate that the soot blowers reach considerable soot that is inaccessible to hand blowing.

Many of the most progressive power plants in the country, especially in the electric-light and railway field, have been using mechanical soot cleaners for years and have placed repeat orders until every boiler is equipped with such blowers, which is evidence that the cleaners must be real soot removers.

The fact that users of the latest improved soot-blowing systems do not go within the settings to remove soot by hand would further indicate that such blowing systems are efficient. In the case of hand blowing, however, it is always necessary to resort to such periodic cleanings.

One of the main troubles experienced in trying to blow soot from boiler tubes by a hand steam lance is the impossibility of using one long enough to reach across the boiler. This results in the soot piling up on the tubes at the far side of the boiler. With the boilers set in batteries, as is the usual practice, it is impossible to overcome this difficulty when blowing the tubes by hand. Even where it is possible to use a lance across the boiler width, this blowing does not clean the sides of the tubes, which play an important part in the evaporation of water.

The soot clings to the tube side, defying removal by hand blowing, and the soot on the tops of the tubes at either side of the blow doors remains untouched. The bulk of the soot that is reached by the hand blowing is really not all removed, but is stirred up and a portion settles on the tubes again. Cleaning the top of a tube prevents some waste, but a properly designed soot cleaner cleans the whole tube surface and is much more efficient.

To further illustrate the losses occasioned by soot on boiler tubes the results obtained at one of the largest electric plants in the country are as follows: Starting with a clean 600-horsepower horizontal water-tube boiler at 50 per cent over rating, the gas temperatures in the uptake were:

	Degrees
First day	550
Second day	575
Third day	600
Fourth day	625
Fifth day	650

These boilers had no blowing system, and in fact were not even blown by hand, and the increase in uptake temperature is significant.

Another test which emphasizes even more strongly the importance soot plays in relation to boiler efficiency, and also illustrates the efficiency of the mechanical soot blower employed, was conducted by recognized engineers at one of the largest electric-lighting plants in the Middle West.

On a new 750-horsepower, water-tube boiler, never before fired, the tubes were blown at the end of the first hour's run and immediately there was a drop of 20 per cent in the uptake temperature. Twelve hours later the tubes were again blown and a drop in the uptake temperature of between 65 and 70 deg. took place. These figures show the effect that soot has on boiler efficiency and also show the importance of frequent and thorough cleaning.

It is stated that with good firing a reduction of 50 deg. F. in the flue temperature will mean a saving of 3 per cent in the coal bill. In connection with this statement, which is acknowledged to be approximately correct, it will be interesting to study the accompanying chart, which was taken at one of the largest cotton mills in Massachusetts.

During the afternoon of the day of the test, experiments were being made with a new grade of coal and new methods of firing, in consequence of which the readings of temperature during the afternoon were erratic. However, accepting the average as shown by this chart, it will be seen that the soot-blowing device, while not receiving all credit due it, still shows marked economy. On the boiler equipped with the mechanical soot blower the chart shows an average reduction in uptake temperature of 77 deg. F. in comparison with the boiler cleaned by hand. This 77 deg. F. reduction represents a 4.6 per cent saving in fuel.

Mechanical soot blowers have been in process of development for the past 10 or 12 years, during which time much valuable experience has naturally been gained by the pioneers in this field. Soot cleaners installed without the proper experience or design back of them can hardly be expected to give the best results.

Most engineers admit that soot defies removal by hand blowing. It is generally admitted that the mechanical soot blower correctly designed, properly installed and intelligently operated is the real solution to the soot problem."

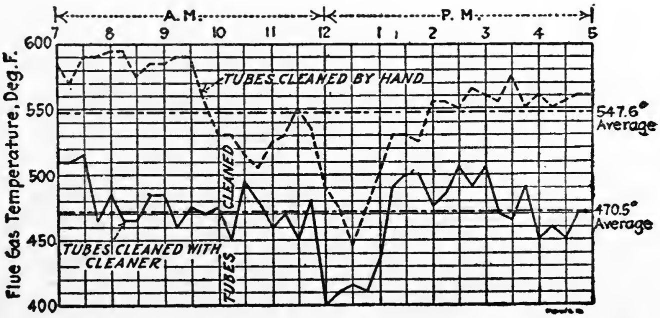


Chart of Temperatures of Flue Gases, With Hand and Cleaner Blown Tubes.

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