SOME REMARKS ON COMBUSTION.

With refererence to the consumption of fuel in ordinary steam boiler furnaces, and to the prevention of smoke.

By E. C. Stables.

INTRODUCTION.

At the present time steam power as applied to almost innumerable purposes, in some form or other, is undoubtedly the most potent agent in forwarding, or even rendering possible, the remarkable progress evident in almost every branch of human industry, and one can hardly realise how universal the dependence on this motive power has become.

Perhaps no more vivid picture of world-wide stagnation and paralysis could be imagined, than that if on a certain date, steam could no longer be produced, and that the giant who ran the factories, and propelled trains and steamships, "annihilating time and distance," was no longer available?

Since the days of Watt an immense amount of study and thought has been given to the perfecting of the steam engine and its boiler, especially during the last few years. The introduction of the "compound engine," and still more recently of the triple and quadruple cylinders, mark distinct eras in the history of the steam engine.

Much thought and talent have been devoted to secure the economical use of steam which is shown by the many improvements in valve gears, &c., while comparatively much less—but still a large amount—of attention has been devoted to the boiler.

That great progress has been made is evident in comparing the common performance of modern steam machinery, in developing one I.H.P. from $1\frac{1}{2}$ lb. of coal per hour, with the former extravagant consumption of fuel; yet, chiefly owing to the competition and the prevailing depression of trade, when only the most economical machinery can be made to pay, still greater economy is continually striven for.

The majority of mechanical engineers, who have charge of boilers and engines, either afloat or ashore, may never be called upon to design either the one or the other, their province evidently being to work the machinery, with which they are entrusted, to the greatest advantage.

The attainment of economy in the production and use of steam, is *evidently based* on the prerequisite perfect and complete combustion of the fuel liberating *all* the heat contained in it, and without attention to this point, no amount of care bestowed *afterwards*, in attempting to secure the thorough absorption by the boiler of the heat generated, or of economy in the use of the steam after reaching the engines, can lead to success.

The writer believes that, notwithstanding the many excellent works published on the chemistry of combustion, that this subject is perhaps *less* studied or understood by many of his brother *working* mechanical engineers than any other branch of their duties. The writer would therefore draw attention, in this paper, to the conditions which must be observed in order to attain "perfect combustion," accompanied by the "prevention of smoke."

Undoubtedly many engineers and firemen have, by dint of long experience, attained great skill in the management of furnaces, without any study of chemistry, yet probably some slight primary knowledge of a few of the plain facts of chemistry might have saved, in such instances, some blind laborious experimenting; for a person working in the dark, without the guidance of theory, is heavily handicapped, and must take many wrong steps.

What is combustion?

Chemists teach that it is simply energetic chemical combination, consisting in the union of the combustible with oxygen. That the amount of energy developed is constant for the same combustible, and is in each case exactly proportional to the amount of fuel burnt; also, that the intensity of the effect depends on the rapidity of the combustion.

The *oxygen* required for the above combination, for all practical purposes (except in the laboratory or in explosives) is, of course, derived from the atmosphere, which, as is well-known, consists of oxygen 21 parts, and nitrogen 79 parts, by volume. The inert nitrogen has no effect upon combustion, except indirectly, by diluting the oxygen, thus hindering its access and union with the combustible; thus greatly increasing the difficulties which, in ordinary practice, attend the proper supply of oxygen to furnaces, by the large increase in volume of the air or gas to be dealt with before, and especially after, combustion.

Lights are extinguished when the proportion of nitrogen in the air is increased by from 5 to 8 per cent., and at the latter point suffocation ensues.

Amongst the variety of combustibles in the Australian colonies, perhaps Newcastle (N.S.W.) co-operative coal may be considered as a fair representative of the fuel in most general use.

This coal has a specific gravity of about 1.3, and after passing through a retort gives from 66 to 67 per cent. of coke, and 33 to 34 per cent. of volatile matter.

Of the volatile matter about 7000 cubic feet per ton of coal, weighing perhaps 245 lbs., remains as permanent illuminating gas; the balance, after condensation appearing as ammoniacal liquor, about 238 lbs.; and tar about 140 lbs., consisting chiefly of liquid hydro-carbons. Of course no condensation of this part of the volatile matter would take place in boiler furnaces.

The ash being from 11 to 12 per cent. of the weight of the coal, when deducted from the percentage of coke, leaves 55 per cent., which may be considered as nearly pure carbon. In ordinary good boiler practice each pound of coal evaporates about 7 lbs. of water.

This coal deteriorates very slowly, and does not apparently suffer as much from exposure to the weather as most kinds of coal, especially the lighter varieties of New Zealand coals.

Having thus briefly touched on the principal components of the combination desired, viz., the union of the carbon and hydrogen with oxygen, the behaviour of the coal when in the furnace may be noticed.

When a fresh charge of coal is put into a furnace on the top of a fire already burned down clear, the first effect is of course partially to damp or smother the fire, especially if, as is usually the case, the green charge is too heavy. Heat is abstracted for the first few moments by the inrush of cold air, and by the warming and drying of the fresh coal, which is perhaps 2,000 degs, F. lower than the previous temperature of the incandescent fuel; but the chief absorption of heat is due to heat being taken up and becoming latent in generating gas from the fresh coal, just as the heat absorbed by the retorts in making gas is used in overcoming molecular attractions, or separating the molecules farther asunder. And it is well known practically in gas works that the coals which give off larger quantities of gas take up more heat in the retorts.

The first effect then of the introduction of a fresh charge of coal into a furnace is to check the development of heat, especially if small coal—lying closer and exposing more surface in proportion to its weight—is used. Thus in cases of very sudden emergency, such as shortness of water, or the crown of a furnace coming down, it may be wiser to smother the fire with green coal or ashes, rather than to attempt to draw the fire at once, for if the fire is heavy the disturbing generates for the time more intense radiant heat, rendering the drawing of the fire both a slow and dangerous process.

After the generation and ignition of the gas from the fresh coal is fairly started, sufficient heat should be given off by the flame—if the requisite oxygen is present—to keep up the gas-making process without abstracting further heat from the incandescent fuel on the bars, just as the heat of a kerosene lamp flame vapourizes and gasifies the oil which supports it.

Besides the volatile part of the coal under consideration, over half of its weight remains incandescent on the furnace bars, and being in a solid state as fixed carbon or coke, the combustion or "union with the oxygen" of this part of the fuel is less rapid than that of the gaseous portion, just as the sweetening of water would be less rapid if a hard lump of sugar were placed in it than if sweet water were added.

J. P. Cooke — Professor of Chemistry in Harvard University—says: "Since carbon, in all its forms, is non-volatile, the molecules of the charcoal cannot leave the solid lumps. They do not, therefore, go half way to meet the oxygen molecules (as the gas molecules do), but simply receive those which are driven against the coals. Hence the process depends on the activity of the oxygen-molecules alone, and, since the number of these molecules which can reach the combustible in a given time is limited by the extent of its surface, it is evident that,—we should greatly increase the rapidity of the combustion by breaking up the lumps, and thus increasing the surface in contact with the gas (oxygen)."

The conversion of the fuel into powder, or further into the gaseous state, is but the partial or complete "breaking up of the lumps."

The general adoption of Siemen's gazogene for the preliminary conversion of the *whole* of the fuel into the gaseous state, greatly as it simplifies and perfects the operations of the furnace, cannot be anticipated for ordinary boiler purposes, as, unfortunately, the apparatus is comparatively cumbrous and the process also, the fuel in the producer being converted apparently at only about one-tenth of the rate of combustion in an ordinary furnace. The writer has recently witnessed the non-success of an experimental gazogene owing to an over-estimate of the rate of conversion.

Oxygen unites with the carbon, or coke, in two proportions: Either two molecules of oxygen unite with one of carbon, forming carbonic di-oxide, otherwise named carbonic acid or carbonic anhydride CO_2, or, if the supply of air is deficient, only one molecule of oxygen unites with each molecule of carbon, thus forming carbonic acid CO.

But it must be remembered that, if the carbonic di-oxide first formed passes again through incandescent coke—as in a thick fire —one of the two molecules of oxygen seizes on another molecule of carbon forming a second volume of the oxide. Thus if the carbon is suffered to pass away to the chimney in the form of oxide half its value as fuel must be lost, and as carbonic oxide is an invisible gas the loss may not be suspected.

The atomic or combining weights of the carbon and oxygen which form the desired oxide are respectively 12 and 32, or 2⅔rds of oxygen to one of carbon, and as oxygen constitutes only ⅕th part of the atmosphere, 5 times that amount, or 13⅓rd lbs. of air, must be required per pound of carbon. Assuming that the coal under consideration contains 55 per cent. of pure solid carbon in the coke; 7⅓rd lbs. of air would therefore be required for the complete combustion of the coke from each pound of coal. The permanent gas—estimated at 7,000 cubic feet per ton of coal at, say, 80 deg. F., or 3⅛th cubic feet per pound of coal—requires for entire combustion 3 times its own bulk of oxygen; the gas from 1 lb. of coal will thus require 3⅓rd lbs. of air. The tar, consisting of condensed hydro-carbons (about 140 lbs. of tar being made per ton of coal charged into retorts), would probably require about another pound of air, amounting altogether to about 11⅔rd lbs. weight, or 170 cubic feet of air at, say, 80 deg. F. per pound of coal.

Tar, weight for weight, is usually considered to have about 1½ times the heating power of coke, and 20 cubic feet of ordinary coal gas are equal to 1 lb. of coal as fuel burnt in a boiler furnace.

Coal gas is only explosive or capable of combustion when it is mixed with air in various proportions; the most explosive mixture is that of one volume of gas to 8 of air, but all mixtures, from 1 of gas to 4 of air to 1 of gas to 14 of air are explosive.

The impossibility of the ignition of coal gas in the absence of air was illustrated on a large scale during the bombardment of Paris, when shells burst inside the gas-holders. In one case the gas was not even ignited; in others the issuing gas was ignited, and burned in a huge jet in the open air.

The coal gas generated in the furnace cannot be ignited below a red heat—perhaps 1,400 deg. F. An iron rod will not ignite the gas issuing from a burner at less than the colour due to about this temperature, and the heat should be maintained above this point within the furnace to ensure ignition of the hydro-carbon gases; or, in other words, the fire should never be smothered with too much coal at once. Benefit is often found by coaling only one side of the fire at a time alternately in moderately large furnaces.

It is evident, then, that more or less of the gases generated in the furnace may go away unconsumed, either owing to a deficiency in the supply of air or oxygen, or by reducing the temperature of the gases below the heat necessary for ignition, or if after ignition before the combustion or union is complete. The chill may be caused by the admission of too much cold air, or by too early abstraction by the boiler of heat from the flame. It is difficult to say which of these causes of loss most widely prevails, but probably in the majority of cases to the latter; for in many instances, in which air is known to be in excess dense smoke is given off and even tarry matter deposited in the tubes, while a low evaporative efficiency is attained.

The "smoke" question may be here briefly dismissed with the remark that almost the whole of the smoke which issues from boiler furnaces is the product of flame prematurely extinguished, therefore any means of preserving the continuance of the flame until the completion of the combustion of the hydro-carbon gases must reduce the quantity of smoke produced.

The attainment of "perfect combustion" is rendered much more rapid and certain by the thorough mixture of the air and gas in proper proportions previous to ignition, as in the Bunsen burner; yet that the combustion of coal gas can be perfect when only the outer layers are in contact with the air is shown by the white and smokeless flame of every gas light. But more time and space are necessary in the case of the plain flame, owing to the smaller surface of the gas exposed for the combination with the oxygen. The value of the close proximity or incorporation of the oxygen with the fuel previous to ignition is illustrated by the greater rapidity and violence of the explosion—or combustion—of nitro-glycerine in comparison with gunpowder. Professor Cooke states that "in the gunpowder the carbon and oxygen atoms are in different molecules, although lying side by side in the same grains; in the nitro-glycerine they are in different parts of the *same molecule.*"

That the abstraction of heat from the flame of a candle prevents the completion of the combustion may be shown by holding around the flame—withont actual contact—a ring half an inch inside diameter, formed on the end of a piece of copper wire say $\frac{1}{8}$ inch in diameter. This abstraction of heat causes the flame to smoke. Doubtless the same thing occurs in all ordinary tubular boilers consuming bituminous coal, as the temperature of the iron boiler tube will be but little above the temperature of the steam in the boiler—perhaps 350 degs.—while the heat of the flame will be at least 1,400 degs.

Sir H. Davy long ago discovered that "a mixture of air and gas would not take fire in a narrow metallic tube, because of the cooling influence exerted by the tube, and that the narrower the tube the shorter the length need be to exert this influence."

Davy further found that "a number of small apertures would not pass an explosion when their depth equalled their diameter." These experiments led up to his invention of the miners' safety lamp.

Professor Tyndall lucidly explains the reason of this extinction of flame, in his grand book, "Heat a Mode of Motion." He says, "A certain temperature is necessary to cause the gas to burn, and by placing wire gauze over the flame, or the flame over the wire gauze, the motion of that light and quivering thing is rapidly taken up by the comparatively heavy metal, which is a good conductor." The best way to avoid this premature extinction of the flame in the tubes of a boiler evidently is to *complete* the combustion of the gas *before* entering the tubes, or in other words to regard the generation of the flame as distinct from the heating of the boiler; the products of completed combustion to be afterwards conducted into the part of the boiler designed to abstract the heat from the gases.

That the fulfilment of these conditions would probably add greatly to the evaporative power of each pound of coal burnt in the majority of boilers, is indicated by the success recorded to have followed the adoption of the gas producer and suitable furnace to boiler purposes in several instances in Europe.

In ordinary practice, especially in marine boilers, the greatest drawback apparently is the want of sufficient space and temperature in the combustion chamber, in which to *complete* the combustion of the gases.

With regard to temperature: The writer has noticed that apparently less smoke was evolved from the boiler of a launch having an external combustion chamber, lined with fire tiles, than from the ordinary type of boiler in which the wet combustion chamber robbed the flame of heat. This evil of the too early abstraction of heat from the flame, is often greatly and unnecessarily increased by building the bridge wall too high, thus cooling the flame by causing it to impinge sharply on the boiler plate, which often suffers from the intense heat. Furnace bridges cannot well be too *low*.

The increased strength of corrugated boiler flues has, since their introduction, permitted furnaces to be made much larger in diameter, without exceeding the maximum thickness of metal admissible, and the additional space afforded between the fuel and the crown of the furnace for the mixing and the commencement of the combustion of the gases, is perhaps one of the best features of modern boilers.

The writer is of opinion, in as far *only* as improved combustion and prevention of smoke is concerned, that benefit would result in most marine boilers if the back, sides, and top of the combustion chamber were cased over with fire tiles; and, further, in the few cases where room could be spared in the combustion chamber, together with ample tube surface, a thin wall might possibly be hung in the combustion chamber, being placed about one-third of the depth of the chamber from the end of the tubes, and extending from near the top of the chamber down to about the level of the ordinary fire bridge. The ignited gases passing thus between red-hot brick walls would have more time and a higher temperature in which to complete combustion before being chilled, and the hanging wall would deflect the furnace gases towards the bottom of the combustion chamber, and the same time tend to thoroughly mix these gases. The practical objection to the hanging wall, such as the choking of the lower tubes, and the want of durabiliiy of the brickwork must, however, prevent its use; but the object sought might be attained in a boiler specially designed. An American patented improvement of boiler furnaces which is now being advertised and pushed, appears to consist chiefly of the insertion of a fire arch *over* the fuel.

Perhaps one of the best examples of a nearly perfect solution of the difficult problem of rapid and *complete* combustion within a limited space is shown by the furnace of a powerful locomotive, in which as much as 150 lbs. weight of fuel per square foot of grate is burned per hour. For instance, as reported in *The Engineer* newspaper of March 20th, 1885: The "Gladstone" locomotive of the L.B.S.C. Railway has evaporated nearly 13 lbs. of water per pound of coal.

The furnace of a large locomotive usually measures about 5 feet in height from the fire bars to the crown of the furnaces. This large space above the fuel—large compared with ordinary marine or internally fixed land boilers—must contribute largely to the success of the furnace, a better opportunity being here offered for the completion of combustion.

The brick arch, placed about half way between the grate and the roof, and which usually extends out from the tube-sheet about five-eighths of the length of the furnace, must in its white hot condition have a highly beneficial effect in mixing and inflaming the gases and the air, and also by lengthening the run of the flame before entering the tubes. Yet without the "arch" the abundant space alone seems satisfactory, as instances are on record of actual loss of economy attending the adoption of the brick arch, although the weight of evidence is greatly in favour of the "arch."

The fire is usually worked so thick in the locomotive furnace that, notwithstanding the sharp draught, not nearly enough air to complete combustion can possibly be drawn *through* the fuel. The supplementary supply of air is then introduced above the fire, through a scoop deflector, and being directed by the deflector downwards on to the fuel, the air mixes with the gas coming from beneath the arch. The resulting flame fills the space above the arch, and combustion is practically completed before the products enter the tubes, which are left to their only proper office of, as it were, sifting the heat out of the passing gases.

The combustion of the coke may either be completed at once by the full supply of air through the furnace bars, or, if the supply of air is restricted, the oxide produced may be burned together with the hydro-carbon gases as in Siemen's system. In practice this question is usually at once decided, as in the case of most boilers it is necessary to force the fires by frequent opening and slicing to pass a surplus of air through the fire, in order to burn sufficient weight of coal in a given time to keep up steam. But the question may remain open in the rare cases where there is sufficient *time* and *space* for the production and combustion of the increased quantity of gas. No doubt the production of the oxide is preferable, for a gas fire is much more under exact control than solid fuel or the ordinary fire of both the coke and gas, which is still more difficult to manage. Much valuable experience of gas fires on a large scale, applied to almost every purpose, must now be accumulating in the natural gas regions of the United States.

If the coke is at the first stage burned to carbonic di-oxide, this gas evolved must, from its well-known power of extinguishing flame, prove very inimical to the continuance of the desired flame in the combustion chamber. This effect is the more apparent when the large quantity of the carbonic acid is considered, as the 0·55 lb. of coke from each pound of coal forms about 2 lbs. of carbonic acid, or, say, about 50 cubic feet, at the furnace temperature.

One would suppose that by the production of the *oxide* from the coke that the hydro-carbon, or coal gas, flame would be in a measure preserved from the injurious presence of the carbonic acid; for the hydro-carbons in the presence of the C.O. having the stronger affinity would first seize on the oxygen if only a limited supply was present. By the addition of a further supply of air later on, the carbonic oxide (being already supplied with one-half of its quantity of oxygen in flames at a lower heat than the coal gas) might be burned *after* the coal gas, at a lower temperature and in a part of the boiler where the hydrogen flame could not exist.

Sir H. Davy states "that the addition of (only) one part of carbonic acid to a mixture of 7 parts of inflamable gas and air in the proper proportions, or of one part of hydrogen with 6 of the mixture, destroys their power of explosion—that is, ignition was prevented."

The combustion of the coke from 1 lb. of coal would produce about 2 lbs. of carbonic acid, and would be accompanied by about 6 lbs. of nitrogen; the ignition of 40 lbs. of the mixture of air and inflamable gas, containing about 2 lbs. of gas, as much as would be generated by, say, 5 lbs. of coal would thus be prevented. The absolute necessity for a large supply of air in excess of the quantity chemically required merely for the *dilution* of the carbonic acid gas is here evident in order to lessen its power of extinguishing flame.

It is probable that the check to combustion offered by the presence of carbonic acid or nitrogen is not due to any inimical property possessed by these gases, but may be solely due to their displacement of the oxygen preventing its access to the fuel. Although nitrogen is incombustible under ordinary circumstances and instantly extinguishes burning bodies, "under certain conditions, however, nitrogen does undergo combustion, as when it is exposed to a very intense heat in the presence of oxygen. This occurs, for instance, when a small quantity of nitrogen is added to a mixture of hydrogen with a somewhat larger proportion of oxygen than is required to form water, and the mixture is then ignited; a loud explosion takes place, and a considerable quantity of nitric acid is formed, owing to combustion of the nitrogen, or, in other words, its union with oxygen."

The great advantage of a thick fire—sufficiently thick to produce some carbonic oxide—is that the supply of air *through* the fire is more regular, and more easily adjusted than with a thin rapid fire, continually burning into holes, through which a large surplus of air is drawn; resulting in loss of heat up the funnel. Apart from the readiness with which a thin fire burns into holes, the difficulty of keeping a large grate surface *evenly* spread, with a thin fire is considerable, and, with most boilers—when a sufficiently sharp draught is available—a reduction of the area of grate surface, and a consequent increase in the thickness of the fire and in the rate of combustion per square foot, is attended usually with increased efficiency and economy of fuel.

Mr. J. T. Milton has stated that "the sharper the draught the less surplus air for dilution of the carbonic acid is required." Therefore with a *sharp* draught less heat is lost by heating air chemically unnecessary.

With a strong natural or forced draught the jets of air entering the furnace at a high velocity must cause strong eddies, and a much more rapid and thorough mixture with the combustible gases ; just as a small strong jet of water directed into a bucket fully penetrates and mixes much more thoroughly than the addition of the same, or a larger, quantity in a slow dull stream. This is probably the chief reason for the increased economy attending forced combustion, to which general attention is now being drawn. So far, however, forced draught appears to have been adopted—as in the case of torpedo boats' boilers—chiefly with a view to secure increased boiler power, comparatively regardless of economy in fuel,—with the old exception in part of the locomotive.

Many years ago, in the early days of forced draught, it was found that with the fan of steam blast applied to a furnace, the air supply might be reduced 25 per cent.

That the slight pressure maintained in a furnace instead of the usual small vacuum caused by the chimney draught of equal power, cannot make much difference in so far as combustion is concerned—although it may make a great difference in the working of the boiler—as witness the case of the locomotive boilers of H.M.S. "Polyphemus," which, with the fires forced by fan blast, primed so insufferably that they had to be taken out of the ship—is proved from the following extract:—

Professor Tyndall found, in the *rarefied* air on the summit of Mont Blanc "that though the light-giving power of the flame of candles was diminished in an extraordinary degree, the rapidity of the combustion (and consequently of the heat given off) was