THE ECONOMIC COMBUSTION OF COAL, AS APPLIED TO STEAM BOILERS.

SMOKE AND ITS ABATEMENT.

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BY L. HEY SHARP, B.SC.

PART I.—GENERAL.

In connection with the subject with which this paper deals, it may, by this time, be said to be practically impossible to bring forward anything radically new. From the very earliest days of the use of coal, the smoke question has been prominent, and the conditions essential to its true economic combustion, have long ago, been definitely ascertained. In the latter part of the eighteenth century, James Watt is found to have given directions for the proper firing of bituminous coal, and, apart from the form of furnace, his advice is perfectly sound to-day. In the first half of the nineteenth century, such men as C. Wye Williams laid down the principles essential to complete economic coal combustion almost as correctly as they may be laid down at the present time, and in late years an immense amount of literature has been published in this connection.

In the face of such facts as these, it is scarcely necessary to remark that fundamental originality is not an aim of the present paper. Its object is rather to summarise as briefly, and yet, at the same time, as completely as possible, all available information of value connected with the title subject. The information has been gleaned from text books, and perhaps, more especially from the numerous papers dealing with the subject in hand, that have been published in various engineering periodicals.

The subject, when considered in all its branches, is a large one, and it is somewhat difficult to know where to set the limits for a paper of this kind. However, it will be seen, that the limits chosen practically provide only for a consideration of furnaces in which coal is burnt on a grate in one or other of the usual ways, the heat produced being directly applied to heating the boiler.

The title employed for a paper of this type is usually something of the nature of "Smoke Prevention," or "Smoke Consumption"; but surely the title used above is the more correct. If the object in view is to attain true economic combustion of coal, the absence of smoke will be incidentally attained as well. On the other hand a mere absence of smoke may be attained in ways that are by no means economic, and accordingly are undesired. Moreover, from the engineer's point of view, the smoke in itself will be seen later to be of very little importance. With regard to the term "Smoke Consumption," even Williams, half a century and more ago, was very sarcastic at the expense of inventors, who, even at that time, were patenting devices for "consuming smoke," instead of attempting to show how to prevent its original formation.

It is not infrequently thought that the attainment of true economic combustion, or even the attainment of merely smokeless combustion, is of necessity accompanied by financial loss. This is by no means the case, and this fact cannot be too strongly emphasised. Actual practice has shown again and again that steps taken to improve furnace conditions result, in general, in financial gain, a gain which may amount to 5, 10, 20, or even a higher percentage of the original coal bill.

Bearing in mind the fact that financial gain may, in general, be expected as a result of proper attention to furnace conditions, and also taking into consideration the age of the subject, it is surely very strange that the properly designed and properly worked furnace is even now very rarely, if ever, met with, at any rate in this part of the world. In the average plant, furnace conditions are, as a rule, crude, to say the least of it, and this, in spite of the fact that, as far as science is concerned, it may be said that in the case of a modern plant there is no excuse whatever, financial or otherwise, for smoke production, and seldom, if ever, any sound excuse for a state of combustion which does not approach to within reasonable limits of perfection.

There is perhaps one thing that is especially responsible for the present state of affairs, namely, that a proper knowledge of the principles of combustion is far from being sufficiently disseminated among those concerned with steam generation. This statement refers not only to the furnace designer and manufacturer, but also to the boiler superintendent and the stoker. Surely under the circumstances such a lack of knowledge is a disgrace to steam users, and when we consider that financial gain is likely to follow, it is a disgrace, and an obstacle, that should be readily eliminated, and should be overcome rather by concerted action on the part of steam users themselves than by Municipal activity.

In a city like Sydney there are, of course, the men who own large batteries of boilers, and then again there are those who own perhaps only one or two steam units. The large steam user may be expected to afford readily the services of an expert to superintend, and give advice concerning his boiler-plant, but the small man can hardly be expected to do this to any really satisfactory extent. Moreover the limited requirements of a few large and, more or less indifferent, firms are hardly likely to encourage the local existence of real experts who will devote their whole time to the subject.

In Hamburg, and also in London, though only recently in the latter city, schemes are in vogue, which have apparently overcome both the above difficulties in a satisfactory manner. The Hamburg Smoke Abatement Society is a voluntary association of steam users, which was formed in 1902 for the purpose of assisting its members in the management of their steam-raising plant. The society employs a staff of expert furnace engineers, whose duty it is to advise members with regard to their boiler plants, and in this way the best available advice may be as readily obtained by the small as by the large steam user.

Next in importance to proper supervision comes the subject of furnace attendance, and this matter, contrary to what is usually thought to be the case, calls for quite as much attention in the case of mechanical stoking, as it does in the case of hand firing. Whatever be the method of stoking employed, the fireman is undoubtedly a most important element in the efficient running of a boiler furnace, and on this account he should certainly have a good working knowledge of the principles of economic coal combustion. In present day practice such knowledge is very rarely found to be one of the qualifications of the fireman; the average fireman is, in fact, little more than an unskilled labourer.

The subject is surely sufficiently simple and straigthforward to be readily mastered by a man of average intelligence. Why, then, should not an efficient course of instruction for firemen be instituted? Such an institution might well be conducted by steam users themselves, through the medium of a society such as that already mentioned, but in any case it would certainly receive their support, because the man who has received a training of this kind would undoubtedly be preferred to the comparatively raw material. The value of the skilled fireman may be emphasised by the following figures:—A fireman will frequently be found to be handling something like six tons of coal per day. This figure is, however, often exceeded, and ten tons per day is not an unknown amount; and in the case of mechanical stoking, even this amount may, of course, be very largely exceeded. It will thus be seen that at Sydney prices, nine times the value of his own wages is quite a moderate estimate of the value of the coal a fireman may be handling, but, even on this estimate, a difference in skill that will save only 4 per cent. in fuel may well be worth an addition of one quarter to the man's pay.

Another useful adjunct to the Hamburg Society is its testing department. This department is fitted up for testing new schemes and ideas evolved in connection with boiler furnaces; and thus members of the society are able to obtain an impartial report on all such new inventions.

The above observations may perhaps appear to be rather a digression; but, on the other hand, they may not be altogether out of place, especially in view of the fact that Sydney has lately been not a little agitated by the smoke question. Such an agitation is, of course, brought about for reasons that do not immediately concern the engineer from a professional point of view. A consideration of the smoke question from the standpoint of the general public would be out of place in the present paper, albeit, it may be worth mentioning that the furnace in which combustion is incomplete, evolves not only the visible, but comparatively harmless, carbon particles, but also certain invisible gases which are extremely injurious to almost all objects, both animate and inanimate, with which they are continually in contact. In fact the harm that may be done by such gases is so serious that it would seem that their escape into the atmosphere should be prevented even at considerable expense; however, fortunately for the general public, the financial accompaniment of proper attention to combustion is, in general, as indicated above, quite the reverse of an expense. The harmful products are invisible, and are not necessarily accompanied by smoke, so that smoke prevention is certainly not the only thing that should be aimed at by those interested in the welfare of the city. Proper attention to combustion obviates the production of smoke, and of all harmful products except one. The exception is sulphur dioxide, the escape of which into the atmosphere can only be prevented by means of scrubbers or some other special method.

Smoke is formed as a result of incomplete combustion of the hydro-carbons contained in the coal. Accordingly, when combustion is imperfect, the flue gases will, in general, be accompanied by smoke, but the real loss from an economic standpoint does not lie in the escape of the particles of carbon which form the visible smoke, but in the escape of unburnt and partially burnt gases, and of heat carried away by excess air. It is to be noted that all these losses in themselves provide no visible indication of their presence. A consideration of the following statement will doubtless lead to a better understanding of how very negligible is the amount of importance to be attached from an economic standpoint to the escape of the smoke itself, that is to say to the escape of the visible particles of carbon:—Experiment has shown that even the backest smoke contains in the form of solid carbon only one-half to three-quarters of one per cent. of the coal supplied to the furnace, whereas steps taken to ensure economic and smokeless combustion have been found to result in a saving exceeding in some cases even 20 or 30 per cent. of the original coal consumption.

There is one serious objection, however, to the formation of smoke, namely that the smoke will coat the heating surfaces of the boiler with a non-conducting layer of soot. In the capacity of a non-conductor, soot is very effective; in fact Mr. C. H. Benjamin states ("Cassier's Magazine," February, 1907), that a layer of soft coal soot is much more effective in checking the transfer of heat than an equal thickness of boiler scale.

Smoke may be considered to be of some importance to the engineer, as an indicator of poor combustion, but even in this respect it is of small moment, for it is by no means an absolute indicator of furnace conditions. This will become clearer later on, suffice it to say for the present, that very poor economy in combustion may be accompanied by a complete absence of smoke.

An accurate idea of the state of combustion can only be obtained by making an analysis of the flue gases; and such an analysis will serve as a measure of furnace efficiency. It may be mentioned in passing that in practice the idea is often entertained that the evaporation per pound of coal is a measure of furnace efficiency, whereas this is certainly not the case. The co-efficient of evaporation, if the term may be used, depends not only on the efficiency of the furnace, but also on the efficiency of the boiler, and on the kind of coal used.

In connection with flue gas analysis, there are various forms of automatic CO_2 recorders or indicators on the market, which are often pushed as being invaluable to the boiler owner. No doubt they have their value; nevertheless, it would be far from correct to suppose that they supply a complete and absolute indication of furnace conditions. This may be illustrated as follows:—The flue gases may show, say, 13 per cent. of carbon dioxide, which is a high value for ordinary practice, but even at this figure there is still room for 6 per cent. of carbon monoxide. This carbon monoxide would pass up the flue unnoticed by the CO_2 indicator, but, for all that, it would represent a loss exceeding 20 per cent. of the total heat value of the fuel. (In addition to the carbon monoxide, unburnt hydro-carbons may also pass undetected up the flue). The subject of flue gas analysis is, strictly speaking, beyond the scope of this paper, and so must be omitted from further consideration.

With regard to smoke prevention, it would seem that there is perhaps one rare case in which a complete absence of smoke may not be attainable in commercial practice, and that is the case of an existing installation where the nature of the plant and existing conditions are such that to make it smokeless would mean unwarrantable expenditure, from an economic standpoint. In such a case an abatement in smoke production may generally be expected under scientific treatment and without unreasonable expenditure. In fact even in these cases such partial treatment appears to frequently result in decided financial gain.

The power plant with an extremely and rapidly varying load is sometimes quoted as an instance in which complete prevention of smoke is not possible. This, however, is not the case. When the load is of this nature there should be especially complete provision for control of the air supply. There should not only be a main flue damper, but also ash-pit and furnace-door dampers. The use of these will be better understood later on.

For the proper combustion of coal the grate area, and in fact the whole of the furnace, should be properly proportioned so that it may not have to be unduly forced. This is a point that is especially liable to escape proper attention in the case of a widely varying load. The rate of combustion that should be allowed varies somewhat with the nature of the coal. The following figures have apparently proved to be good practice; but, of course, they are only approximate, for in addition to class of coal there are many other conditions such as available draught, percentage of ash, percentage of sulphur, and so on, which enter into the problem: they may, however, be of value as a guide to those interested in furnaces.—

Anthracite, 15lbs. per sq. ft. of grate surface.
Semi-anthracite, 16lbs. per sq. ft. of grate surface.
Semi-bituminous, 18lbs. per sq. ft. of grate surface.
Bituminous, 20-30lbs. per sq. ft. of grate surface.

Part II.—The Principles of Economic Coal Combustion.

The principle constituents of coal are carbon and hydrogen. The carbon is present partly in the form of solid or, so called, fixed carbon, and partly in cobination with hydrogen, with which it forms compounds known as hydro-carbons. Of these, methane (CH_4) ethylene (C_2H_4) and acetylene (C_2H_2) may be mentioned as important examples. There are also other elements present in coal, such as oxygen, nitrogen, sulphur and silicon, but for the purposes of a paper of this kind their presence may be practically overlooked.

Of the hydro-carbons contained in coal, some are solid at ordinary temperatures, but many are liquid or gaseous, and all are gaseous at furnace temperatures. As constituents of solid coal their form of physical state and chemical combination is not yet fully understood. However, as far as we are now concerned, coal may be regarded as a mixture of solid carbon and gaseous hydro-carbons; albeit, the evolution of the latter as gas or vapour from the solid coal is accompanied by the absorption of a certain amount of heat, but this will be referred to again later on.

It is the hydro-carbon portion of the coal, and not the solid carbon, which causes the difficulty in burning coal without smoke; and, apart from the question of smoke, it is these same hydro-carbons which bring about by far the greater part of the difficulty of procuring the complete economic combustion of coal on a boiler grate.

The solid or fixed carbon unites in the process of combustion with the oxygen of the air before it rises from the bars of the grate, and then rises in the form of invisible, gaseous carbon monoxide or carbon dioxide. Once in either of these forms it is never reduced again, within the furnace or flues, to the solid state. It is thus clear that this portion of the coal cannot produce smoke; however, on the other hand, its combustion may be very incomplete. To indicate this latter point as graphically as possible, figures will be quoted and reference must be made to the following well-worn chemical equations for the combustion of carbon with oxygen:—

$$C_2 + O_2 = 2CO \quad \dots \quad \dots \quad (1)$$

$$2CO + O_2 = 2CO_2 \quad \dots \quad \dots \quad (2)$$

Equation (1) illustrates the re-action which takes place when each molecule of solid carbon combines with a molecule of gaseous oxygen, which is, of course, the active constituent of air, to form two molecules of colourless gaseous carbon monoxide. If sufficient oxygen is present a further action will take place, and this is illustrated by equation; (2) the two molecules of carbon monoxide will combine with a further molecule of oxygen to form two molecules of carbon dioxide.

Both the above reactions are accompanied by an evolution of heat. One pound of carbon, when oxidised to carbon monoxide, yields in the process approximately 4440 British Thermal Units, and if the monoxide thus formed be further oxidized to dioxide an additional 10,080 units of heat will be evolved. It will thus be seen that if the carbon be merely oxidised to the monoxide very nearly 70 per cent. of the total