PRESIDENTIAL ADDRESS

NOTES ON MODERN BOILERS

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During the last fifteen years boilers for power stations and industrial plants have undergone many changes, and the purpose of this paper is to outline in a general way some of the features of modern steam-raising units and their associated equipment.

It is not possible for a paper such as this to cover the entire field of present day boiler practice. Any attempt to do so would involve a mass of detail and complex technical data which would take many months to prepare; and in any case the necessary data for dealing fully with the subject are not available in this country, where opportunities for checking calculations by results obtained with experimental equipment are limited.

Boilermakers and the authorities in charge of power supply and development overseas spend large sums of money in the laboratory and on the construction of experimental plants, with the object of improving the quality and performance of steam-generating equipment. They employ highly skilled technicians and observers, whose duty is to be fully informed concerning developments elsewhere, and to translate theory and experiment into commercial usages.

The trend of modern power stations is towards increased boiler output and higher efficiencies, and in order to meet the demand it has been necessary to adopt higher pressures and temperatures. The development of higher pressures and temperatures has been somewhat rapid; but practice and experience are overtaking theory and hypothesis, and it is now possible to anticipate with reasonable accuracy the average conditions of service under which any component part of a boiler installation operates. Higher boiler pressure does not involve any material revision of the physical properties of the material used for the construction of the pressure parts. Commercial steels of standard boiler quality are suitable for pressures up to critical pressure of steam; this statement perhaps requires some qualification regarding the effect of temperatures, but reference to this point will be made later.

To meet the demand for higher pressures, boilermakers furnished an Oliver for Roland by developing fusion welded
boiler drums and solid forged boiler drums, which are suitable in every way for any pressure likely to be adopted for commercial undertakings. With increasing pressures it is, of course, imperative to avoid any inequalities of stress, and to ensure uniformity of contour for walls exposed to pressure and heat. Any condition conducive to breathing is dangerous, and internal stresses must be eliminated as far as practical by normalising and annealing. Fusion welded and forged pressure parts are eminently suitable for high pressures from every point of view. It should be mentioned that normalising is performed at 650° C. or thereabouts. For complete normalising the temperature should be increased to 950° C., but this temperature involves risk of distortion, so it is preferable to use the lower temperature, at which only slight inherent stresses remain. These are insignificant compared with the dangers consequent upon distortion.

Whilst boilers have undergone some very important changes in themselves, methods of manufacture have also undergone drastic changes. The construction of a modern boiler is no longer a blacksmith’s job. It is now comparable with turbine work, and requires the highest attention to detail in order that the availability of the boiler will be at least equal to turbine availability. Some power stations are of the one-boiler one-turbine type, and in such cases it is essential for the boiler to be constructed so as to go into line with the turbine from the point of view of reliability and availability.

For pressures up to 450 lbs. per sq. inch, boiler drums are usually of rivetted construction or of fusion welded construction. From that pressure upward fusion welded or forged seamless drums are employed.

The material employed for the drums must conform strictly with the standard specified by the boiler inspection authorities, both as regards chemical analysis and physical properties. Test pieces are taken from each plate for analysis and examination, and if the test pieces fail to meet with the requirements of elongation or tensile tests, and if analysis shows nonconformity with the approved standards, the parent plate is rejected.

Possibly the most interesting method of drum construction is fusion welding of the metallic arc process. This method makes use of a suitably coated electrode, and the heat of the arc is not only sufficient to melt the ends of the electrode, but also to fuse, the surface of the work being welded over a small area. During welding it is necessary to protect the work from contamination of the atmosphere, and this is done by using a flux-coated electrode which confines the gases involved around
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the arc, as the flux cutting is fused at the electrode tip; a certain amount of further protection is provided for the formation of slag.

Welding operators on pressure work should be efficient and skilful and thoroughly trained, and should be put on to high pressure work only after considerable experience. Direct current is considered superior to alternating current for welding of pressure vessels. All welds are examined by X-ray for the detection of cracks, slag inclusion, and lack of penetration; and after completion of welding the drums are heat-treated for stress relieving.

Solid drums undergo most minute inspection, and eight test specimens are furnished from each longitudinal seam for examination and testing purposes. The manufacturer is required to give the boiler inspection authorities notice when the following stages of manufacture are reached:—

(a) When test plates are ready for stamping, before they are cut from parent plate.
(b) When the plates are bent to form, welding grooves machined, and parts assembled ready for welding.
(c) When welding is in process.
(d) When welding at the outside surface has been completed and the inside surface has been prepared for welding.
(e) When seams are dressed.
(f) When test plates are ready for the cutting off of test pieces, and when the test pieces have been machined ready for test.
(g) When the openings are prepared for stand pipes and seatings, and during welding on of these.
(i) When the drums have been heat treated prior to hydrostatic test.
(j) When the drum is ready for hydrostatic test.
(k) When the tubes holes are bored and the drum is completed.

The above conditions are laid down by the Association of the Offices Technical Committee, representing the leading Boiler Insurance Companies of Great Britain.

Whilst appropriate design for high pressure is not difficult to accomplish without departure from standard material of construction, the effect of high temperatures calls for more careful consideration. The limiting steam temperature for
Ordinary imported steel is about 850° F., and for various alloys it is about 1000° F. The higher efficiencies and fuel saving incidental to high steam temperatures are to some extent offset by the cost of the special material of construction for the heating elements and the cost of maintenance and replacements. At 1200° F. the life of alloys is about three and a half times the life of ordinary carbon steel, but it is problematical whether one offers any advantage over the other. Some engineers favour ordinary steels at lower cost with frequent replacements, while others prefer the higher priced alloys which give longer periods of service.

Oxidation occurs on the inside of mild steel superheater tubes at temperatures above 850° F., and this increases the resistance to heat transfer, with consequent increase in metal temperatures. Whether alloy steels under high temperature conditions will give the same periods of service and availability that are being obtained at lower temperatures with ordinary steels has not been definitely established; and this might be important when considering economic temperature conditions for some boiler installations. This does not apply where alloys are subject to fairly favourable conditions, and when they are protected from direct radiation.

Steam temperatures above 800° F. require some form of temperature control. One form of temperature control is by means of dampers arranged for bypassing the superheater with part of the hot gases. These dampers can be arranged for automatic regulation by means of an electric motor with thermostatic control; such automatic control will maintain a temperature within the limits of plus or minus 15 degrees.

Another means of superheat control is to recirculate a portion of the gases from a cooler zone in the boiler setting, and to mix these with the hot gases passing over the superheater surface. Here again automatic control will maintain the temperature of the steam within the limits mentioned above. This method is perhaps the best of all forms of superheat control, as it eliminates the dampers, which are liable to distortion and wastage due to continued contact with very high temperature gases.

A further alternative for controlling superheat is the provision of a de-superheater; but this form of control is costly, and it involves additional pressure parts to operate at boiler pressure where boiler pressures might be anywhere in the range of 600 to 1800 lbs. per sq. inch. The cost of any additional pressure parts is considerable, and might easily increase the cost of the installation by 10% to 15%, without offering any great advantage in return for the extra cost.
As boiler pressure increases, natural circulation becomes sluggish, owing to the increased weight of steam reducing the difference of weight between steam and water. Self evaporation occurs under these conditions, and it is now usual to employ unheated downcomers arranged out of the gas flow to stimulate circulation, and thus avoid overheating and possible failure of the tubes. An example of unheated downcomers will be found on the large radiant heat boilers now being installed at the Newport "B2" Power Station for the State Electricity Commission of Victoria. These downcomers comprise a number of tubes arranged outside of the boiler brickwork on each side of the boiler setting; the steam and mud drums being extended to accommodate them.

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Forced and controlled circulation overcomes the difficulty of circulation in high pressure boilers; as, with this type of boiler the water is circulated through the boiler tubes at about three times the rate of maximum evaporation, and the continuous delivery of water past the heating surface is assured. With this type of boiler it is not necessary to provide a free and natural outlet for the steam from the tube heating surface to the steam space. Surging and priming do not occur in forced circulation boilers.

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For a given evaporation the forced circulation type boiler requires only half of the space occupied by the natural circulation boiler, and its weight is approximately half the weight of the old-fashioned type. Comparing the weights of three types of boilers, in each case the boilers being suitable for an evaporation of 66,000/77,000 lbs. of steam per hour:

- Horizontal Tube Type Natural Circulation Boiler = 97 tons
- Vertical Tube Type Natural Circulation Boiler = 81 tons
- La Mont Forced Circulation Boiler = 46 tons

The largest forced circulation type of boiler yet installed is the La Mont boiler at the West Deptford Power Station of the London Power Company. This boiler evaporates continuously 350,000 lbs. steam per hour at 400 lbs. per sq. inch pressure with a final steam temperature of 850°F.

The principle of the La Mont boiler is as follows:

It comprises a steam and water drum from which the water is taken through a suction pipe to circulating pumps, by means of which it is discharged into distributing headers. From the
headers it is distributed through the steam-generating tubes by means of special orifices or nozzles, one of these orifices being inserted at the entrance to every tube. The size of the nozzle is carefully designed in order to ensure that the correct amount of water is distributed to each generating tube.

The amount of water circulated greatly exceeds the amount of steam generated. This assists in the separation of steam from water. The circulating pumps operate at constant speed for all boiler ratings. The forced circulation is a logical development of water-tube boilers, in just the same way as mechanically forced and controlled draught has been proved essential for the intensive and efficient combustion of fuel; and it is quite reasonable to expect that in ten years' time the only type of boiler likely to receive serious consideration by steam users is the forced circulation type of boiler.

The release of heat in the boiler furnace for absorption by the heat utilising services is influenced by various factors. Combustion has, of course, to be self-supporting, and the rate of extraction must not exceed the rate of evolution. The modern boiler furnace is designed with due regard to the effect on combustion of exposed coal surfaces, the characteristics of the fuel and fusion point of residual ash.

With old-fashioned boiler settings heat releases of 80,000/90,000 B.T.U.’s per cubic foot of furnace volume were common, but with modern boilers equipped with large combustion chambers the heat release adopted is generally very much lower than that. In the cases of completely water cooled furnace walls, a heat release of 30,000 to 40,000 B.T.U.’s is usual for stoker-fired boilers, and for pulverised fuel fired boilers the heat release is 20,000/30,000 B.T.U.’s per cubic foot. With refractory walls heat release of 20,000/30,000 B.T.U.’s is usual for stoker firing, and 12,000/15,000 per cubic foot for pulverised fuel firing.

The boiler furnace is the focal point of boiler economics. It is the cost-producing factor in service, and it also materially affects capital cost of any installation according to its size. The characteristics of the fuel and fusion point of ash have to be carefully considered in order to promote appropriate ignition of the fuel and avoidance of trouble due to clinkering and slag. It is, of course, desirable that furnace temperatures should be as near as practical to the maximum for reasons of low fuel cost and for savings in first cost of construction. On the other hand there are the considerations of continuity of service and elimination of undue maintenance costs. Higher furnace ratings than those mentioned above are common in forced circu-
lation boilers, also in natural circulation boilers with closely pitched wall screen tubes, also when the fusing point of ash is high; but in such cases some form of turbulence is introduced into the furnace, such as tangential firing for pulverising fuel burners and overfire air jets at pressures varying from 8 in. water gauge to 24 in. water gauge for stoker firing.

The heat absorbing and utilising surfaces are classified as follow:—

- Water Walls
- Boiler
- Superheater
- Economiser
- Air Heater

and various combinations of these or all of them are normally incorporated in a modern steam-generating unit, the extent of each class of heating surface being governed by circumstances as the final steam temperature required, initial feed water temperature, cost of fuel, etc.

Water walls absorb heat by radiation, and produce steam at rates up to 70 lbs. per sq. foot of area per hour.

The boiler surface takes up heat by convection, and in addition to a certain amount of heat by radiation, and produces steam at rates up to 11 lbs. per square foot of surface per hour.

Superheater surface takes up heat by convection normally, and absorbs heat at rates of from 3000 to 4000 B.T.U.'s per square foot per hour, and under the same conditions, but at lower temperatures the air heater surface absorbs heat at about 800 to 1000 B.T.U.’s per hour.

It would take a large amount of boiler heating surface to reduce the gas temperature to an appropriate terminal temperature. For example, in a boiler of 5000 square feet heating surface evaporating 25,000 lbs. of steam per hour, 90% of the work is done by the first 50% of boiler surface. The first half of the boiler heating surface will reduce the gas temperature to 1000° F. or thereabouts, and the last half will reduce the gas temperature by a further 400° F. to 600° F. In order to reduce the gas temperature by another 150° F. to a terminal temperature of 450° F, the heating surface of this boiler would require to be increased 100% or thereabouts.

Actually it is not possible for a boiler to reduce the temperature of the gases to the economical temperature, and the useful limit of boiler surface is about the point where the gas temperature is reduced to 700° F. to 800° F. To attempt extending the usefulness of boiler surface beyond this point is a mistake,
as it only prolongs a process which descends in efficiency as it extends, and the lines of mean temperatures for water and gas approach the point when they become parallel, after which, of course, no further transfer of heat takes place.

The proper and logical method of attaining the desired terminal temperature for the gases is to employ the lower-priced economiser or air heater surface for the heat recovery required for this purpose. The cooler surface of an economiser or air heater restores the temperature gradient, and makes further heat recovery easy to accomplish and at much lower cost than one can be done with boiler surface.

Whether the gases should be reduced to the terminal temperature by an economiser or by an air heater or a combination of the two, depends upon the thermal characteristics of the plant. If the initial feed water temperature is very high the usefulness of an economiser is limited, although a steaming economiser will to some extent alleviate this disability.

With gases entering the economiser at 700° F., and an initial feed water temperature of 300° F., the economiser would reduce the temperature of the gas by about 200° F., and increase the temperature of the feed water by about 90° F. on an economical basis, while with a lower initial feed water temperature its economical value and heat-absorbing capacity are proportionately increased.

The air heater is unaffected by initial feed temperature considerations, because it is dealing with air at constant low temperatures. Basing upon inlet gas temperature of 800° F. and air at 70° F., the gas temperature could be reduced to 300° F. quite easily, thus giving an air temperature at the air heater outlet of 630° F. Allowing 30° F. duct losses, the air would be introduced into the furnace at 600° F., and this would increase the furnace temperature by 200° F. or 250° F. Intensification of the furnace temperature by the use of preheated air improves combustion; it accelerates the burning of fixed carbon, and reduces the unburnt residue. What is perhaps more important is that the heat-absorbing surfaces directly exposed to radiation from the fuel bed absorb heat at greatly increased rates, and the boiler rating is increased without reduction in efficiency.

Increased boiler output due to increase in heat transfer by convection is negligible, and to secure any material increase of such the gas velocity would need to be so high and with such abnormal draught losses that the cost of power for driving the draught plant would be greater than any saving due to the gain in heat transfer.
To obtain maximum boiler output it is necessary to intensify the furnace temperature, and thus take advantage of the high rates of heat transfer attendant upon direct radiation.

The importance of heat utilising surfaces exposed to direct radiation rests upon the extraordinary rate of heat emission from incandescent carbon, which is an almost perfect black body, and also upon the fact that water-cooled surfaces exposed to such heat emission can absorb it without overheating. The heat transfer in B.T.U.’s per square foot by radiation is:

\[
1600 \left[ \left( \frac{T_1}{1000} \right)^4 - \left( \frac{T_2}{1000} \right)^4 \right]
\]

\( T_1 \) = temperature of furnace in °F. absolute.
\( T_2 \) = temperature of tube in °F. absolute.

In the case of a boiler setting this expression requires some qualification for angle of radiation, the condition of heat receiving surfaces, etc., and also because some heat is additionally transferred by conduction and convection from the turbulent and flowing gases.

The transfer of heat by convection is approximately proportional to mass velocity and the difference in temperature between the gas and boiler surface. The amount of heat transferred in this manner may be expressed by:

\[
H = R (T - t)
\]

when

\( R \) = B.T.U. per sq. ft. per hour °F. difference.
\( T \) = mean temperature of gas.
\( t \) = temperature of surface.

\( R \) is commonly termed the coefficient of transfer, and a number of factors have an important bearing on its value; consequently it is not advisable to assume any hard and fast value for it, as it includes the effects of mass velocity, hydraulic depth, and specific heat and density of the gas and water.

Some authorities give the value of \( R \) as follows:

\( R = a + b w \)

where

\( a \) = constant proportional to conductivity.
\( b \) = a constant proportional to specific heat and temperature.
\( w \) = mass flow per unit area.

The practical value of \( a + b w \) appears to vary between 4.5 and 7 B.T.U. per hour per sq. ft. per °F. difference.
Much has been written and said concerning heat transfer in boilers, and as this paper is intended to be general in character, a passing reference to heat transfer is appropriate. It is not possible for a paper such as this to set out exact law and formulae to cover fully the functions of heat transfer; for as each individual case must be considered separately and in accordance with its own particular circumstances, and sometimes these circumstances are most extraordinary.

The first law of thermo-dynamics says that the loss of heat by one body is equal to the gain of heat by its associated part, but phenomena sometimes occur in practice which are definitely contradictory to this law. In practice instances sometimes occur where heat is taken up by a cold fluid in contact with hot gases, and the temperature of the fluid is increased materially without corresponding fall in the temperature of the hot gas. This gain of heat is unaccountable according to any of the established laws, and is no doubt due to some obscure process such as the burning of hydrogen or some chemical or mechanical reaction which is not as yet fully understood.

The point is that it sometimes happens that the accepted laws of thermo-dynamics do not coincide with ascertained facts, and it is possible that these will lead eventually to modification of the standards at present adopted for the determination and testing of boiler performances.

A few years ago a single boiler unit evaporating 50,000 or 60,000 lbs. steam per hour was considered a large unit, and an output of 100,000 lbs. of steam from one unit was considered most noteworthy. Nowadays 100,000 lb. units are smaller than are usually found in power station work, and the tendency is towards units capable singly of a continuous evaporation of 300,000 to 700,000 lbs. steam per hour, and it will be of interest to note the marked improvement in efficiency now being obtained with higher boiler ratings compared with those of earlier date and lower boiler ratings. Fifty years ago, with Lancashire boilers, 65% efficiency was accepted as being satisfactory performance. With a development of water-tube boilers the efficiency was increased to 70%, and then later to 75%. Nowadays it is usual for quite a small boiler plant to operate at an efficiency of 82% to 84%.

A good example of the advances made in boiler practice is provided by an order recently placed in England by one of the electricity authorities for boiler house equipment. This contract provides for the installation of four boiler units, each capable of evaporating 150,000 lbs. steam per hour at 1400 lbs.
per sq. inch working pressure, and a final temperature of the steam 960° F. The guaranteed efficiency of the plant is 89% on the gross calorific value of the fuel.

It will be realised that a performance such as this could not possibly be obtained without closest attention to the details of the boiler and also its associated equipment, and everything connected with it, down to the smallest auxiliary, should be in quality, reliability, and standard of workmanship equal to those of the boiler itself.

The valves employed in a boiler installation such as that mentioned above call for special attention in order to be suitable for the pressure and temperature conditions they have to withstand. In addition to withstanding effects of pressure and heat, the valves are subject to mechanical shocks and the wear and tear according to their position and conditions of service.

Cast steel valves are no longer considered suitable for very high pressures, and the trend is for valves to be of pressed steel construction, with working parts constructed of special alloy. Some authorities recommend that valves for high pressures and high temperatures should be constructed with special alloy bodies, and whilst this suggestion has not been put into universal use, it has much to recommend it. Safety valves particularly require close attention on high pressure boilers and these are subjected to very rigid and searching tests in order to ensure full compliance with regulations, particularly in regard to accumulation tests.

Pipework associated with high pressures and temperatures also calls for care in design and layout; details of this class of pipework are no longer taken for granted, and it requires more than a simple measurement between two terminals to determine the appropriate dimensions for any pipe. The internal stresses set up by expansion under working conditions are carefully calculated, and an appropriate amount of cold springing is allowed for in order to reduce the stress set up when the pipework is heated up. The tendency is to keep joints down to a minimum, and the use of flash welded joints in lieu of flanged or other types of joints is becoming prevalent.

Flanged connections where employed on high pressure work are provided with ground and scraped surfaces, and are finished off with welded seals.

Pipework supports should be designed to allow flexibility and to accommodate movement of the pipes under working conditions, the pipework being rigidly fixed only at the anchors.
Soot blowers are universally adopted for removing soot from boiler superheater tubes. Steam is the medium employed for this purpose, although experiments have been made with air and water in place of steam, but up to date these have not justified departure from the use of steam.

Soot blowers are usually hand operated, and are in the form of jet tubes arranged across and between the tube banks, or in the form of retractable type blowers termed "gun" blowers. The jet tube type revolves through an arc of anything up to 360° in order to sweep the tubes within range, whilst the gun blowers are capable of movement through a cone having an angle of approximately 45°.

Some attention has been given to automatic control of soot blowers, having a simple push button station on an instrument panel for electrical control, which brings the various elements into service and operation in their proper order, but so far this practice has not appeared outside of one or two of the largest power stations in the world, where the matter of operating soot blowers on very large units is of considerable importance. Suitable soot-blowing equipment will increase boiler efficiency by anything up to 5%, and in some cases where dirty fuel is used considerably more. They are relatively inexpensive and amply justify their inclusion in any boiler installation, as more often than not they will pay for themselves in the first year of service out of savings effected in the fuel bill.

Soot blowers will not, of course, remove slag incrustations from boiler tubes. This requires something more definite than steam jets. Experiments have been made with the use of various compounds injected into the furnace for the removal of slag, but so far the results obtained from these experiments have been negligible.

The object of this paper has been to outline in a general way some of the methods employed in the construction and operation of a modern steam-raising plant. Ordinarily such a paper should have dealt with boiler house auxiliary plant, such as draught equipment, automatic coal and ash handling plants, boiler house layout, but unfortunately circumstances precluded this. Nevertheless the writer hopes that his comments will prove of some interest to members.
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Notes on modern boilers (Presidential Address 1939)

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File Description:
Notes on modern boilers (Presidential Address 1939)