FOSSIL FUEL FIRED BOILER WATER–STEAM SYSTEM

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Contents

Summary

Furnace design depends upon a number of factors. There is the overall size and geometry, since the ratio of absorption area to furnace volume changes with an increase in size. Then there is the burnout time for the fuel and hence the flame length. Another

factor is the ash fusion temperature as the ash must not contact boiler or superheater tubes while molten or semi-molten. This dictates the temperature at which the exhaust gases should leave the radiant furnace and enter the convective passes. This temperature in turn indicates the division of heat absorption between these two parts of the boiler. Evaporation of water generally occurs in the radiant furnace, and superheating and reheating of the steam in the convective passes. In large high-pressure boilers with a high degree of superheat and reheat, there is insufficient heat absorption in the convective passes and some superheating (or reheating) must occur in the radiant zone. This leads to a further complication, as the characteristics of superheaters exposed to radiant heat and convective heat are different. Both superheaters and reheaters need to be positioned so that their outlet temperatures remain reasonably steady over a range of loads.

Changes in load on the boiler alter the division of heat absorption between the radiant and convective passes, and hence the final steam temperatures. Various methods are employed to control steam temperature, some directly and some indirectly by varying the balance of heat absorption. In addition to load change requirements, some method of varying heat absorption is invariably used so as to compensate for ash fouling of the boiler tubes, which may upset the balance of heat absorption.

Water circulation through the water walls of the radiant furnace is usually by natural circulation, but may be forced by a pump to increase the capacity. Separation of the generated steam from the water is usually accomplished by cyclone separators to ensure effective separation at high flow rates. However, in supercritical boilers there is no density difference between the water and steam and the once-through system of circulation must be adopted.

1. Furnace Design

1.1. General Principles

The design of the furnace generally dictates the configuration of the entire steam-generating unit. All large units have vertical furnaces in which burnout of the fuel occurs in a vertical direction regardless of the direction in which the fuel is injected. The upward motion is promoted by the natural buoyancy created as the fuel burns in the preheated but cooler surrounding combustion air. This creates symmetry, with a hot central combustion zone that radiates heat uniformly to the surrounding water walls. The flame should never impinge upon the walls and the fuel should have burned out completely before the hot gases leave the furnace. All pulverized-fuel-fired boilers have relatively large furnaces with bare water walls. There is the general principle that the volume of the furnace increases with the cube but the surface area increases with only the square of the linear dimension. This leads to a disproportional relationship between furnace volume and water-wall surface as boiler size increases. The standard configuration with a single furnace is therefore practical only up to an equivalent electrical output of about 750 MW. Therefore, for very large capacities a center wall is built into the furnace space to create two separate furnaces. Without changing the total volume or external dimensions this increases the surface area receiving radiant heat by about a third.

The number and arrangement of the burners and the type of fuel being used dictate the size of the furnace itself. With wall burners there must be adequate spacing between the burners horizontally and vertically to ensure that the flame envelopes do not interfere with one another. With both wall and corner burners there must be sufficient clearance between the combustion zone and the water walls to avoid flame impingement. The furnace space above the flame must also be adequate to ensure complete combustion and sufficient cooling of the ash before the hot gases enter the convection pass. The furnace exit gas temperature is quite critical with regard to the potential for slagging as, at too high a temperature, the ash is semi-molten and sticky and quickly fouls the convection pass tubes. Furnace height, and consequently furnace volume, therefore increase with fuels having a longer burnout time and with ash having a lower fusion temperature. Oil-fired furnaces can therefore be quite compact but coal-fired furnaces need to be rather tall. With coal-fired furnaces there is also always a small amount of oversize pulverized fuel that requires additional burnout and cooling time.

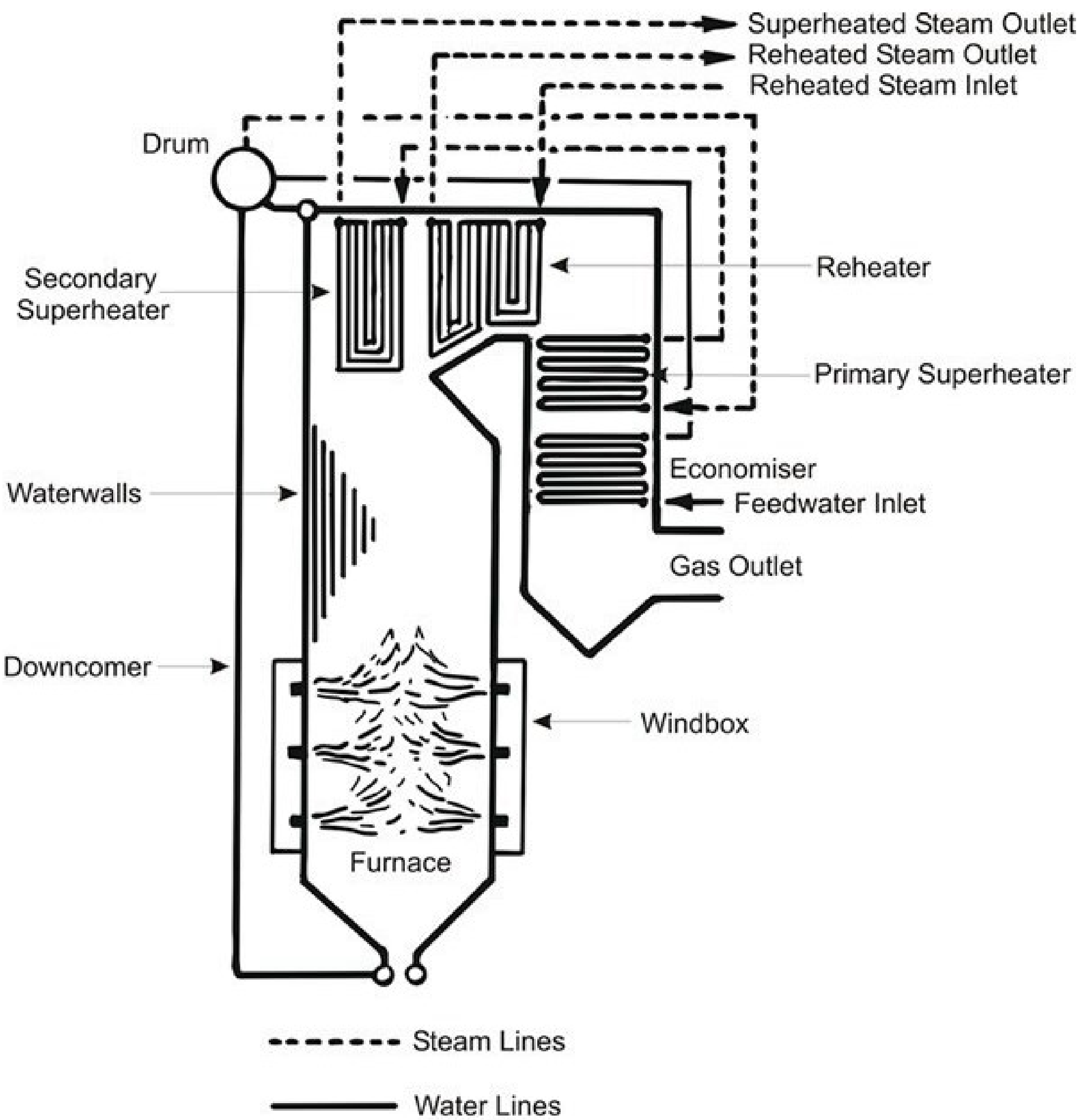

Figure 1. Typical boiler heat absorption components

A further point of consideration is the relative heat absorption between the water walls and the convection pass. Generally, water evaporation occurs in the water walls whereas water preheating and steam superheating and reheating occur in the convection pass. This allows for the highest rates of heat transfer to occur around the combustion zone of the furnace since the highest heat transfer rates occur during the boiling process. With boilers operating at low pressures and moderate steam temperatures, a large portion of the total heat received is required for water evaporation. In such cases, some evaporation may be arranged to take place in the convection pass. This requires an appropriately designed steaming economizer. At the other extreme, with boilers operating at high pressures and high steam temperatures, a large portion of the heat received is required for steam superheating and reheating. This change in heat absorption is not only due to the additional heat going into superheating and reheating but also to the lesser amount of latent heat required to evaporate a given mass of water at higher pressures. Figure 1 shows diagrammatically the heat absorption components of a typical boiler and the water and steam interconnections between these components.

A number of factors need to be taken into account in the design of a furnace. The required output dictates the number of burners to give the necessary heat release rate. The type of fuel dictates the arrangement and spacing of the burners, and hence the volume of the combustion zone. The burnout time of the fuel and ash fusion temperature affects the height of the furnace. With the combustion gases having to be cooled to an acceptable furnace exit gas temperature, the balance between heat given up by the gases in the furnace and in the convection pass is fixed. This may not match the heat absorbed by water evaporation and steam superheating and reheating. In fact, in coal-fired boilers with tall furnaces and operating at high steam pressures and temperatures, there is usually insufficient heat in the gases after leaving the furnace to provide the necessary superheating and reheating. For these boilers some superheating is done within the furnace zone by radiant heat. These superheaters may replace the water walls in the upper part or roof of the furnace or may hang down as “platens” in the top of the furnace.

Although the design of steam-generating units has become very standardized, the design of each individual unit has to be tailored to match the type of fuel being burned. This is particularly the case when burning coal. Combustion and fouling problems in coal-fired boilers are often due to a mismatch between the coal characteristics and the furnace design.

1.2. Ash Characteristics

Ash characteristics have a major impact on furnace design. With all methods of suspension firing, the bulk of the ash is carried out of the furnace with the combustion products. For pulverized coal, about 80% generally leaves with the combustion gases and 20% collects in the furnace hopper. Typical coals contain 10% to 20% ash but some can have as little as 2% or as much as 40%. Lignites have an ash content of 50% or more. Although heavy fuel oil has a relatively low ash content of 0.5% or less, the same principles apply. Consider a typical steam-generating unit with an equivalent electrical capacity of 500 MW, burning coal with 20% ash. About 10 kg s^{-1} of ash will be produced and of this about 8 kg s^{-1} will be carried through the convection pass with the remaining 2 kg s^{-1} collecting in the ash hopper. At this rate the convection pass and downstream ash collection system has to handle about 28 tonnes of ash per hour. Any tendency for this ash to abrade or adhere to the convection pass tubes will have dramatic effects on the boiler integrity and performance.

Combustion of coal particles in suspension produces tiny globules of molten ash, which harden into tiny spheres. Comparison of the size distribution of the particles of this fly ash and that of the original pulverized coal leads one to believe that, during the release of volatiles and oxidation of the carbon, there is further fragmentation of the particles. The resultant fly ash has a particle size of around 10 microns but with many smaller particles down to about 1 micron. Since most particles are small, light, and spherical they are not abrasive as such, but some impurities in the coal may produce larger, more abrasive particles.

The ash fusion temperature, that is the temperature at which the ash particles solidify, is critical to the satisfactory performance of the boiler. Ash that is above the fusion temperature will adhere to any surfaces with which it comes into contact. This causes a build up of slag within that part of the furnace. If it is sufficiently fluid at that temperature it will run down and collect in a cooler part of the furnace.

Ash that is below the fusion temperature may collect simply as dust on a surface in its path. This may be removed relatively easily by routine sootblowing. Ash deposits, however, act as insulators and change the heat absorption characteristics of any part on which they build up. Thus dry ash that may collect on the furnace walls may subsequently liquefy due to the radiant heat received from the furnace not being removed as effectively by the water-cooled walls because of the insulating effect of the underlying ash.

A coal producing an ash with too low an ash fusion temperature will not be suitable for pulverized fuel firing as the furnace exit gas temperature will have to be too low, and, even in the furnace, slagging problems may arise. A cyclone furnace with a slag tap to drain the molten ash is more suitable for such fuels.

The ash fusion temperature varies with the chemical composition of the coal. The mineral matter in the coal is generally in the form of oxides, each with a characteristic melting temperature. At elevated temperatures these oxides interact in a complex manner that usually results in a lower melting temperature. In such a mixture an increasing percentage of acidic compounds or very high or very low percentages of basic compounds raise the fusion temperature. Thus, a "slagging index" may be defined as the ratio of basic to acidic components in the ash:

$$R_{basic\,/\,acidic} = (Fe_2\,O_3 + Ca\,O + Mg\,O + Na_2\,O + K_2\,O) \,/\, (Si\,O_2 + Al_2\,O_3 + Ti\,O_2) \quad (1)$$

This ratio allows the comparison of one coal with another, assessing their relative fusion temperatures and potential for causing slagging problems in the furnace. However, there are other contributing factors such as the silica/alumina ratio, the iron/calcium ratio, and iron/dolomite ratio which all affect the ash fusion temperature. Some coals have ash that is very high in specific compounds such as ferric oxide, silica, or alkalis that further affect the ash fusion temperature.

The temperature at which ash melts may be tested by setting a small pyramid of ash in an oven and heating it at a prescribed rate. The initial deformation temperature is the temperature at which rounding of the tip begins.

This is the ash fusion temperature at which it becomes sticky and will adhere to boiler tubes or other components. Other temperatures are defined by observation of the shape of the pyramid until the flow temperature is reached. At this temperature the ash has become molten and, in practice, the molten ash or slag will flow from the furnace.

2. Water Circulation

2.1. Water Wall Configuration

On large steam-generating units the entire furnace is enclosed by water-cooled walls that absorb the intense heat radiation from the combustion zone. These walls consist of tubes of about 50 mm in diameter linked together by narrow bars welded to the tubes.

The tubes and bars thus form a continuous impervious wall, one side of which is exposed to the furnace while the other side is suitably insulated to prevent heat loss. Radiant heat received by the bars between the tubes is transferred to the adjacent tubes by conduction so that the entire wall is an effective absorber of heat.

Where there are wall burners, soot blowers, or instrument windows the tubes are bent sideways and folded behind one another to create an opening, as shown in Figure 2. At the bottom and top, the tubes are connected to transverse headers that respectively distribute and collect the water entering and leaving the tubes.

Usually the front and back walls of the boiler are sloped inwards at the bottom to direct falling ash into an ash collection hopper. The back wall of the furnace may be similarly shaped at the top of the furnace to direct the hot combustion gases into the convection pass. At the top of the furnace, however, the headers have to be arranged to provide a free upward flow of water to the boiler drum where the steam can be separated.

The boiler drum is usually the highest major component of the boiler. From the boiler drum a few large pipes or “downcomers” direct the water down to the headers at the bottom of the furnace.

The boiler drum and water walls are suspended from the top of the boiler supporting structure and the walls are hung like curtains during assembly. In operation, the water walls expand downwards when heated, resulting in a movement of several centimeters at the bottom. To give the water walls rigidity, large transverse steel beams or “buckstays” are fixed to the walls at intervals over the full height of the furnace zone. They are designed to prevent inward or outward buckling of the walls during furnace pressure transients.

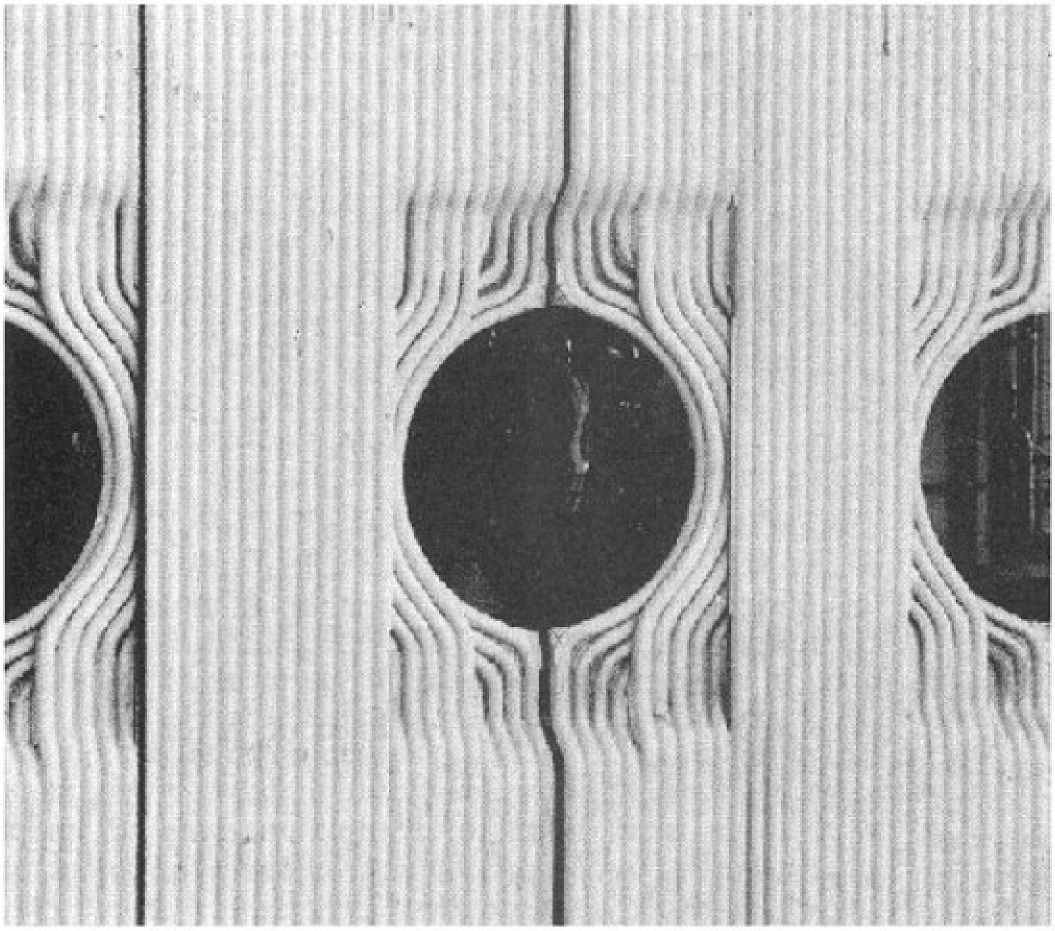

Figure 2. Boiler water walls showing burner openings (courtesy of Babcock and Wilcox)

The furnace usually operates under a slightly negative pressure to prevent egress of combustion products, but combustion instability can impose pressure transients which, when applied over such a large area as the side of a furnace, can create very large forces.

The outside of the water walls is lagged with several centimeters of mineral fiber insulation, usually slightly compressed into blanket form and held in place by wire mesh and studs attached to the walls. This in turn is clad with corrugated aluminum or galvanized steel sheeting to give a neat and durable covering to the boiler. Figure 3 shows the construction of a boiler water wall.

There is naturally some heat loss through the walls but, in a large boiler, this is only a fraction of a percent of the total heat generated at full load. The heat loss is generally constant for all load conditions since the temperature of the water in the tubes is practically the same at all loads.

Most boilers rely on the natural buoyancy of the steam generated in the tubes to promote circulation in the tubes. This establishes the basic concept of vertical boiler tubes and upward flow towards the boiler drum and imposes some constraints on the arrangement of the tubes. In supercritical boilers, however, there are no phase change buoyancy effects and all flow must be mechanically driven. This allows more freedom in the arrangement of the boiler tubes, which may be divided into separate sections where the heat absorption rates are different or laid at an angle across the furnace walls, as in the spiral-wall furnace.

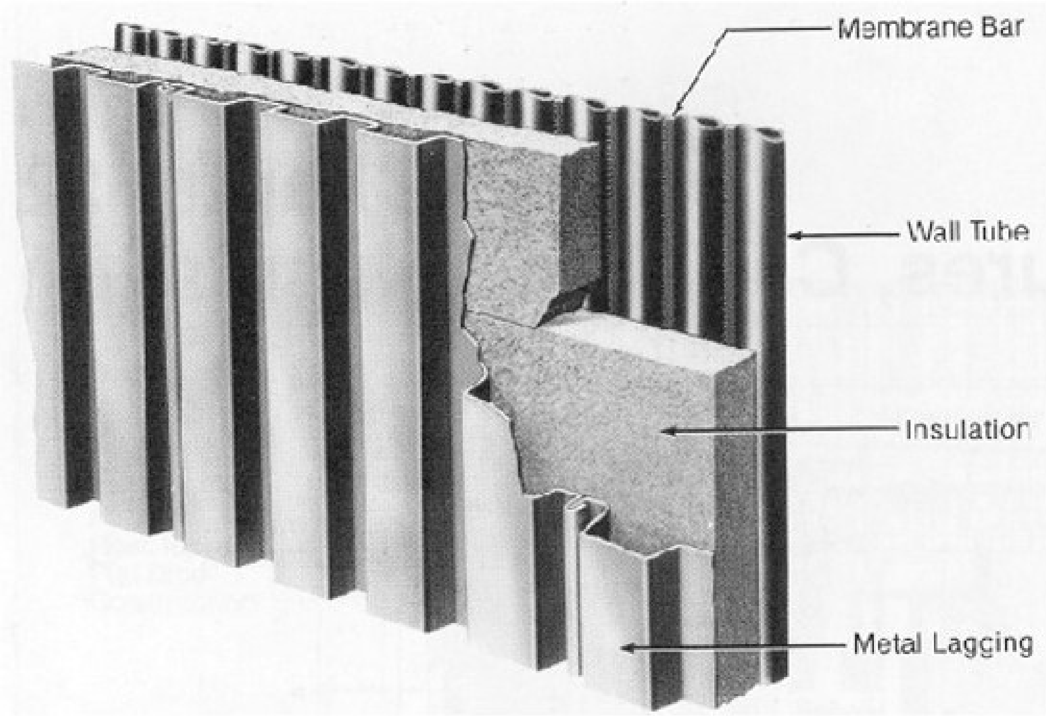

Figure 3. Boiler water wall construction (courtesy of Babcock and Wilcox)

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from the University of Cape Town. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom, and obtained an M.Sc. in nuclear engineering from Imperial College, London University. On returning and taking up a position in the head office of Eskom he spent some twelve years there, initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of the Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa, being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation, he obtained a Ph.D. in mechanical engineering from Queen's University in Canada. He was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick, where he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and teaching of courses in both nuclear and non-nuclear aspects of the program.