FOSSIL FUEL FIRED BOILER PLANT CONFIGURATION

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Summary

Steam generating units or simply boilers as well as nuclear steam supply systems produce large quantities of steam at high temperatures and pressures. This steam is used in steam turbines to generate electric power. The steam generating unit is thus a major component of a thermal power plant. Following a rapid evolution in size during the

middle of the twentieth century the current capacities for coal fired units are around 700 MW electrical although units up to about 1300 MW electrical are feasible. Once the efficiency of a typical steam cycle is taken into account the heat release rates due to combustion in the boilers are some two and a half times this value.

For fossil fuel fired boilers this requires a very large furnace in which to burn fuel at a high mass flow rate. The fuel, whether solid or liquid, has to be finely divided and mixed with air to promote rapid combustion. For coal fired plants, the coal must be pulverised to a fine powder in suitable pulverising mills. Large quantities of ash are produced and this has to be collected for disposal. Coal fired boilers therefore require substantial auxiliary equipment to support the basic combustion process. Even oil fired boilers require special fuel handling equipment. All types use vast quantities of combustion air and hence need suitable fans to feed in the air and remove the exhaust gas. The incoming air has to be heated and the exhaust gas cleaned to ensure good combustion efficiency and minimal environmental pollution.

In order for modern fossil fuel fired boilers to meet current emission standards in industrialised countries, gas cleanup facilities must be provided. In coal fired boilers a substantial quantity of fly ash must be removed from the exhaust gas. Depending upon the sulphur content of the fuel, desulfurization units may need to be installed to remove sulphur dioxide and, in many densely populated areas, nitrogen oxides may need to be removed as well. These additional back-end components of the boiler plant increase the complexity and cost of a power plant but are necessary to maintain good environmental conditions.

1. Introduction

1.1 Terminology

In fossil fuel fired thermal power plants, that part of the plant which produces the steam to drive the turbine is known as the *boiler plant* or simply the *boiler*. Since boiling is only one of the several processes that occur in this part of the plant a more correct term for it is *steam generating unit*. This term is more explicit in stating its purpose while at the same time implying the incorporation of various auxiliary systems which contribute to the production of steam. In nuclear fuelled thermal power plants the correct term for the equivalent part of the plant is *nuclear steam supply system.*

1.2 Development

The development of steam engines can be traced back three centuries. With their development came the need for steam production but, due to limitations in materials, steam could not be produced at pressures much above atmospheric. Early steam engines thus operated by vacuum caused by the condensation of steam in a cylinder. As materials improved, steam pressures increased and, in the next century, steam engines and steam locomotives were at the forefront of power production. During the last century steam boilers and steam turbines evolved to become the largest continuous power producers. Present day boilers of the water tube type go back at least a century and have been continually developed and refined into the efficient and sophisticated units currently in service. Materials are still one of limiting factors in further development and interestingly the combustion of some fossil fuels is still somewhat of an art rather than a science.

1.3 Capacity and Size

Plants built during the early part of the past century generally had a series of boilers feeding a common steam main which in turn fed a series of turbines. This minimised the impact of forced shutdowns of any of the boilers on the overall production of the plant. In the latter part of the past century improved reliability of boilers allowed the linking of individual boilers and turbines as single units without interconnecting steam lines between the units. Boiler capacities then had to match the requirements of the turbine. This is now common practice for units in the capacity range from about 100 MW electrical to about 1300 MW electrical. The latter size is however unusual and many large fossil fuel fired boilers currently in operation are around 700 MW electrical.

1.4 Efficiencies

There is economy of scale in building large units. For example two units of half the size have a higher total capital cost than a single unit of the original size. Large units are also usually more efficient as heat losses can be minimised and efficiency improving features more easily justified. The efficiencies of most modern steam generating units are high having reached a sort of plateau. The major thermal loss is in the exhaust gases being discharged to the atmosphere.

2. Basic Design

2.1 Fundamentals

A steam generating unit consists essentially of a combustion zone in which fuel is burnt to release heat and a heat exchange zone where heat from the hot gases is transferred to the water and steam. Fuel must be supplied to the combustion zone in a form in which it can be readily ignited and completely burnt within an acceptable time frame. Air must also be supplied to the combustion zone in such a way as to promote rapid and complete combustion but not in excessive quantities.

After combustion the hot combustion gases must be directed to the heat exchange zone and finally discharged to the atmosphere. Within the heat exchange zone the hot gases transfer heat to the water and steam. Ideally this would be a large counterflow heat exchanger with subcooled water entering where the gases are relatively cool and with superheated steam leaving where the gases are hottest. There are however limitations with this arrangement. Firstly the intensity of the radiant heat flux from the combustion zone can only be sustained by water cooled walls.

Secondly without some initial cooling, the very high temperatures of the gases produced in the combustion zone would be too high for heat exchanger tube banks carrying steam. As illustrated in Figure 1 the combustion zone therefore is surrounded by water walls in which steam is generated. The partially cooled hot gases then enter the superheater and reheater tube banks above the furnace at the top of the boiler structure. Finally, when relatively cool, the hot gases pass through the economiser at the back of the furnace and which preheats the incoming subcooled water. It is evident then that the combustion zone and heat exchange zones are integrated and that the resultant arrangement is not ideal from a heat exchange point of view. The material limitations which force heat to be transferred across a large temperature difference results in a substantial loss in available work potential in all fossil boilers.

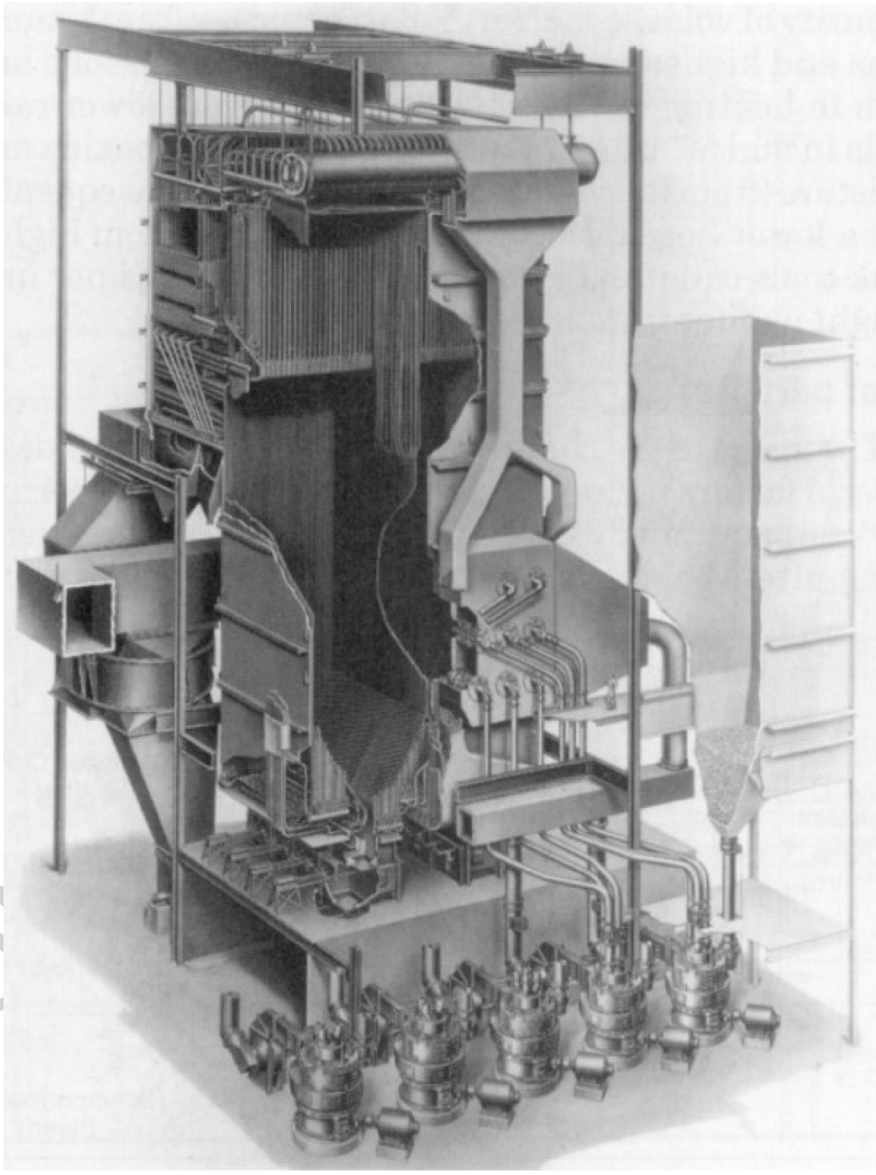

Figure 1 Cut away view of pulversied coal fired boiler (courtesy of Babcock & Wilcox)

2.2 Thermodynamic Guidelines

Material limitations prevent the production of steam above about 560°C although slightly higher temperatures are possible with special steel alloys. This effectively sets an upper limit to the temperature of the thermodynamic cycle and hence a maximum possible Carnot cycle efficiency. If the pressure in the boiler is increased the temperature at which heat is added during evaporation is also increased. As the average temperature at which heat is added to the working fluid is increased, the cycle efficiency increases. Thus it is advantageous to increase the boiler pressure as much as possible. There are however practical limitations as boiler components have to be sufficiently robust to withstand the high pressures. From a thermodynamic point of view it is a case of diminishing returns because, at very high pressures, a given pressure increase will yield a lesser efficiency improvement than at lower pressures but still require the same capital investment to increase the thickness of all pressure components. The generally accepted maximum economical pressure is just above the critical point somewhere around 26 MPa. Just below the critical point pressure of 22 MPa there is the problem of separation of steam from the water as there is insufficient density difference. To overcome this problem the maximum pressure at which *circulating* boilers with steam separating drums can operate is about 16 MPa. Between 16 MPa and 26 MPa *universal pressure* or *once-through* boilers must be used. In these the water is progressively and completely evaporated to steam while passing through any tube in the boiler only once. Most large utility boilers currently in service are circulating boilers and operate at about 16 MPa and 540°C.

Under these limiting conditions the steam system will have a certain Rankine cycle efficiency. This efficiency can be improved by reheating the steam after partial expansion in the turbine. During reheating heat is added at elevated temperatures so that the average temperature at which heat is received by the working fluid is increased. The efficiency of a reheated cycle is thus higher than that of the basic superheated cycle. Reheating also has benefits for the turbine which should not operate with an exhaust steam quality of less than about 90 percent. The reheat pressure is usually between 20 percent and 25 percent of the initial superheat pressure. Double reheating can be employed but the gain in efficiency is hardly worth the additional capital expenditure of running a second set of steam pipes from the turbine to the boiler and back.

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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.