Appendix - I

General Technological Information about Boilers and the Factors which Influence Thermal Energy Efficiency

Boiler is the basic equipment system which provide steam to different process functions. As such the boiler is an equipment/device which generate steam for process heat, power/electricity generation and hot water. The boiler consists of two important component units, i.e. (a) the furnace (heat generating units) which burn on different fuels like coal, lignite, oil, gas, fuel wood, charcoal, agrowaste etc., and (b) the boiler (through a heat transfer mechanism to form a pressure vessel). There are package and external furnace and vessel systems. In a package system, the furnace and boiler/vessel together form an integrated whole and in an external system vessel boiler and furnace are separate different systems.

The boilers can be classified in a multi-dimensional pattern such as:

(a) Position (stationary/mobile)
(b) Pressure (low pressure/high pressure)
(c) Materials used (cast iron boiler, steel boiler, copper tube boiler)
(d) Tube contents (fire tube boiler/water tube boiler)
(e) Firing system (fired or unfired pressure vessel)
(f) Fuel used (liquid fuel/solid fuel)
(g) Package/non-package (furnace and boiler integrated/separate)
(h) Shape (horizontal/vertical).

Though such a variety of classifications can be given, the following classification are the ones more commonly used.

(a) Package boilers
(b) Lancashire boilers
(c) Fluidised bed combustion (FBC) boilers

Package Boilers: Package boilers are of two types. Fire tube types and water tube types.
Fire Tube Types: In fire tube package boilers furnace and boiler/vessel systems are in the same unit. It is a versatile type of boiler which can use/burn solid fuels like coal, lignite, agrowaste, fuel wood, charcoal and liquid fuels like oil (LSHS, fuel oil). This type of boiler consists of a combustion chambers from where the hot flue gases goes into the large flue tubes where heat transfer take place due to radiation. As the temperature drops below 1000°C, the flue gases are made to pass through small smoke tubes where most of the heat transfer is convective. The steam pressures of package boilers are upto 20 kg/cm² and beyond this limit it may turn uneconomical. These types of boilers give 70 to 80% efficiency.

Water Tube Package Boilers

Water tube boilers are of two types, the one having straight tube and the other bent tube. The straight tube types are more convenient and economical because of low draft loss, accessibility of tubes from inside and outside, easiness of tube replacement. Also straight tube boilers gives pressure slightly higher than flue tube boilers. Bent tube boilers, on the other hand, gives high pressures and heat. These are more suited for larger capacities and thereby greater economies of operations are possible. The efficiency of water tube boilers is, (other factors remaining the same) usually between 75% to 80%. Like fire tube boilers, these types of boilers are also fuel versatile capable of burning liquid and solid fuels.

Externally Heated Lancashire Boilers

In lancashire boiler heating take place externally and steam is heated primarily by radiative heat transfer process. Usually Lancashire boilers are shell-type. It is capable of producing larger quantities of steam at moderately high pressure depending upon the particular process need and design parameters. It consists of two wide flues which first pass through the length of a cylindrical drum, then back through outside the bottom of the drum and afterwards through the two flues to the stack. The two wide flues within the drum contain the space for combustion and allow some transfer of heat from the hot combustion products to the water in the drum. More heat transfer take place during the passage of the gases around and outside of the drum. However, much of the heat evolved during the combustion is lost as sensible heat in the gases at the base of the stack. It is because of this technological/design limitation the Lancashire boiler turn out to be energy inefficient, giving efficiency only upto 55-60%. It is not a fuel mix
versatile boiler like package and FBC boilers. Usually Lancashire boiler is coal, lignite, agrowaste and fuel wood fed. Compared to all other boiler systems, lancashire boiler is energy inefficient and environmentally unfriendly (The experimental details proving this phenomenon is discussed in Chapter 5).

**Fluidised Bed Combustion (FBC) Boilers**

Fluidised Bed Combustion (FBC) boiler technology is exactly the environmentally friendly and economically viable boiler technology which can be identified as an important sustainable development energy technology. FBC boilers efficiently combust/burn inferior fuels having high ash and sulphur content and emit less SO$_2$, NO, and SPM (See the experimental result in Chapter 5). At the same time it also gives efficiency more than 80%. However, FBC system consume more electricity as electricity using coal crusher is an unavoidable component of this system. The initial investment needed for this system is also almost three times more than the investment needed for package boiler system, giving a long payback period compared to package boiler system. Yet this technology is the only environmentally friendly boiler technology so far evolved.

The basic principle governing the FBC technology is that of flowing a gas through a bed of particles so that the bed of particles takes on fluid-like properties. Good mixing of particles promoted by such air bubbling and turbulent action provides excellent conditions for an efficient combustion of variety of gaseous, liquid and solid fuels. For example when coal is mixed with hot invert particles bubbled in this fashion, it get distributed uniformly and as a result a full and complete burning process take place. As the bubbling bed is highly agitated and turbulent and heat transfer surface is immersed in such a turbulent bed a very high rate of heat transfer to the boiler vessel take place, resulting in high efficiency. It is also possible during this process to create a situation/opportunity for a chemical reaction between the sulphur in the fuel and sulphur absorbing material to be added so that gaseous sulphur emission can be prevented. Further, it is also possible to obtain uniform temperature throughout the bed (burning region). (When suitable quantities of dolomite or lime-stone are added to the turbulent bed a major part of sulphur present in the coal can be retained in the bed, thereby reducing SO$_2$ emission/pollution). Though FBC has got a turbulent burning region (bed), the maximum temperature varies between 750-950°C and as a result emission of oxides of nitrogen (NO$_x$) and trace elements
are reduced significantly. Because of such a temperature condition slag or clinker is not formed and volatilization of alkali salt which cause fouling and corrosion of boiler tubes is also reduced to a greater extent.

There are two types of fluidised bed. One that of bubbling bed and the other circulating bed. In the bubbling type of fluidised bed, fluidising velocity of between 1.5 to 3.5 m/sec. is used. In the circulating bed system the entire bed is moved like a pneumatic transport system. The hot bed material passes through refractory lined cyclone separating clean gas from the bed material. The hot bed material is recycled by cooling through another bubbling bed where heat is used for steam generation. The main combustion chamber is water walled and the clean hot gasses are passed through a convection which is more or less similar to conventional boilers. The inert medium (usually ash or sand or any such inert particles which are compatible with the fuel particles used) has to be heated to a temperature of about 600°C using auxiliary heating system before the fuel can be burned in the fluidised bed. The bed can be heated by a flame above the bed while fluidising with cold air or passing hot gases through the bed.

The air distributing system is an important component in the FBC boiler and it consists of a number of bubble caps/nozzles in which there are holes and slots at the top of the nozzles. This system plays a major role in deciding the efficient combustion process, and hence the total efficiency. Another advantageous aspect of FBC is, both water tube and fire/flue tube boilers can use fluidised bed combustion technique successfully and thereby having the benefit of a hybrid technology. Thus, FBC technology is the one boiler technology which can be identified as supportive to sustainable development process.

Air Pre-heating System

The air temperature fed to the boiler plays a significant role in determine the ultimate boiler efficiency. Hence, if the input air is pre-heated the fuel consumption of the boiler can be reduced. The air pre-heater is, therefore, considered as a supportive system device for any type of boilers. Usually air pre-heating system is one conventional recuperative device having both shell and tube shape. As the heat transfer coefficient for air and gas is very low, the air pre-heaters regions large heating surface. Therefore, the space and cost considerations sometimes becomes a discouraging factor in
adopting pre-heating systems. The issue is that such cost should be less than the additional energy conservation benefit accrued.

Water Pre-heating System (Economizer)

As the pre-heated boiler input air help reduce fuel consumption in the boiler, pre-heated boiler water also help reduce the ultimate fuel consumption and therefore an increased boiler efficiency. Water pre-heating systems are also called economizer. Economizers pre-heat water before entering the drum of the boiler. Economizer is a system attached to the main boiler system operating on the waste heat emerging from the main boiler. Thus, economizer is a system which help use the waste heat economically and thereby reducing the entropy loss of energy to the atmosphere and at the same time increase the total energy efficiency of a boiler.

Input Factors which affect Boiler Efficiency

Irrespective of technological variation, i.e., modern or traditional, the boiler efficiency is also depending upon the physical, chemical and thermal characteristics of the different boiler inputs like fuel, water and air. For example the unoptimal moisture content, increased ash content and impurities reduces the classific value of the fuel. Also other chemical characteristics content like carbon, hydrogen, sulphur, nitrogen etc. involved in the fuel input, liquid or solid, also have a pivotal role in deciding calorific value of the given fuel, hence, the boiler efficiency.

As stated earlier, the thermal status of the air and water inputs directed to boilers also have a role in determining the ultimate/total efficiency of the boiler system. When the cool air enter the combustion region (burner), a part of the energy from the heat generated is absorbed by the cool air, reducing the thermal efficiency. When such reduction take place it necessitate increased consumption of fuel. It is because of this reason an air-preheating device is provided for increasing the boiler efficiency. Likewise, the thermal status of the boiler water is also an important parameter in determining the ultimate boiler efficiency. When cool boiler water needs more energy, comparatively hot water require less energy. For example, the boiler input water coming through economizer is already heated and hence the steaming process inside the boiler vessel is evolved rapidly without requiring much energy to get it heated up inside the vessel. As the energy for the economizer is coming from the waste heat from the stack the
entire boiler steam producing process becomes more energy efficient, resulting in less fuel demand. Thus, calorie values and impurities of the input fuel, temperature status of the air and water inputs etc. are important attributes of ultimate/total boiler efficiency, other than technology.

Steam Distribution System and Insulation

Significant losses of steam occur during the distribution and transit process. The metallurgical, insulation and engineering/network status of the pipe line system plays an important role in the steam loss or saving process. Piping systems need to be insulated to prevent heat and steam loss. Leakage usually occurs at connections in the pipe and valves used to control steam. Loss also occurs at devices called steam traps (However, the intensity of these losses depend upon the pressure factors of the steam passing through the pipes). Therefore, a major opportunity for steam energy saving is insulation and distribution management of the steam network system. The insulation is so important that often the area exposed by the pipeline system is much more than the boiler and heat losses from the surfaces of the pipe line due to radiation and convection, is very high. Hence, the ultimate/total energy efficiency can be optimised through efficient steam distribution management, especially insulation.

Boiler Operation and Management Aspects

The total boiler operation and management is in fact, the most important thermal energy management function aiming at total efficiency. This include maintaining optimum air-fuel ratio, fuel loading and optimum design capacity utilisation, flue gas status monitoring, controlling the shut down frequency, scale removing, skill expertise of the boiler personnel.

Air-fuel Ratio

To realize efficient and complete combustion a specific ratio of air to fuel is required. If there is too little air the fuel is incompletely burnt and its full heat content is not realised and also more carbon monoxide is released due to incomplete burning causing air pollution. On the other hand with too much air valuable heat from the fuel is carried off into the flue by the excess air. The fuel to air ratio, therefore, needs to be controlled very precisely between very narrow range/limits. The usual practice is that the incomplete combustion is considered less of an evil than huge loss of
heat (from an economic point of view) and burners/boilers are operated with little less air. When economically this practice is acceptable, environmentally it is not, as such practices contribute to enhance air pollution. To avoid such energy loss and pollution gain, the boiler system should undergo regular flue gas analysis. From flue gas analysis it is possible to identify the optimum air-fuel ratio. Sophisticated electronic flue gas analyzers are now available (experimental results obtained from flue gas analysis using electronic flue gas analyzer is presented in Chapter 6). Thus, air-fuel ratio is one of the important parameter which determine both energy efficiency and air pollution.

Fuel Loading and Design Capacity Utilisation

The maximum efficiency of a boiler is attained when it is operated close to its design capacity. Boilers which are operating at low load, i.e., below 30% of the design capacity will be very inefficient and the steam produced will be very expensive. There are three common circumstances where poor boiler loading or under design capacity utilization leads to total boiler inefficiency: (a) When there are more than one boiler and the load is unevenly distributed, i.e., one boiler is loaded upto design capacity and the other is loaded partially (because of the full design capacity operation, the second boiler is not needed), the inefficiency of the total boiler system leads to a total energy inefficiency. Such a situation can be avoided by optimizing the production process and eliminating the partially loaded boiler (b) Another type of waste/inefficiency occurs when the steam demand for different operations vary in a day and the boiler is compelled to operate under design capacity. This type of wastage also can be avoided through process scheduling and optimization. (c) A third kind of inefficiency happens when the boiler and steam distribution system was originally installed/designed to meet a large/high demand and afterwards compelled to have a low steam demand because of the total under capacity utilization of the very unit itself. Thus, fuel loading and design capacity related efficiency or inefficiency is more a function of the full capacity utilization, and diurnal variation in production process and optimum operation of boiler and steam management.

Flue Gas Status Monitoring

As stated earlier, continuous flue gas characteristics monitoring can lead to significant energy saving. When the incomplete combustion take place the
emission of CO will be more and that of CO₂ will be less. This undesirable situation can be avoided by maintaining the optimum air-fuel ratio. However, such a correction can be incorporated only if the flue gas status/characteristics is continuously monitored through a continuous flue gas analysis process. Computer integrated flue gas analyses are available, but such systems are rarely in operation at present in India.

Scale Removing and Maintenance

Irrespective of all the factors explained above, which affect boiler/steam efficiency, the scale forming in the boiler tubes due to bad water quality (hard water and water containing carbonates) can leads to an increased energy loss. Because, when sealing take place more heat is required as the scale sediment also absorb a part of heat and the tube surface could be heated up only after the scale segment get heated sufficiently. This type of energy loss or inefficiency can be completely avoided through regular practice of scale removing and also providing treated water to the boiler. Fortunately, in situ scale formation preventing scalometers are available and many progressive units are using the same.

Human/Personnel aspects which affect Boiler Efficiency

Probably one of the most important factor which affect the boiler efficiency is the human/personnel factor. Training, expertise alertness and the sincerity of the boiler operator/personnel can contribute very significantly in realizing energy efficiency. There are two aspects of it. In the manually operated boilers, boiler operators feed the fuel and also remove the ashes manually. Often partially burned coal is removed from the bottom as ash and as a result sometimes significant part of fuel is lost. Also, the optimization of the air-fuel ratio in the manually operated boilers are, to a greater extent, depending upon the experience and expertise of the boiler operator who can identify the optimality condition because of his experience and practical knowledge. One unfortunate fact is that not only a majority of the boiler operators are not having adequate general education, but also basic energy education. Further, they are heavily under paid and working under physically very uncomfortable conditions. As a result they are totally dissatisfied and often do a half-heated work. All the above factors combined may result into a vicious circle of total thermal energy inefficiency of the boiler system, especially in the traditional manually operated boilers.
In the case of boilers which are technologically sophisticated the energy inefficiency attributed to human factor is slightly different, especially in case of fluidised bed combustion boilers. Though most of the operations like fuel feeding and ash ejection are automatic, the boiler operator needs sophisticated training to efficiently operate FBC boiler systems. Also the general education level of the operator has to be moderately high so as to enable him to sufficiently grasp the advanced technological nature and operational procedures of such boilers. There is a great dearth of trained operators at present, and as a result, many of the FBC systems are facing acute shortage of trained operators and hence many FBC systems are operated by less trained and inexperienced operators, ultimately leading to operational problems including energy in-efficiency. Thus, operation and managerial attributes of boilers plays a very significant role in attaining total energy efficiency both in case of traditional and modern technologically advanced boiler systems.