BOILERS OPERATION & MAINTENANCE

23-27/12/2007

1 Overview

1.1 Introduction

A Boiler is an important unit operation, widely used in oil refinery, petrochemical and power industries. It utilizes the combustion energy of fuel to generate steam, which is used in various equipment in the plant.

In the following figure a simple boiler unit is depicted.

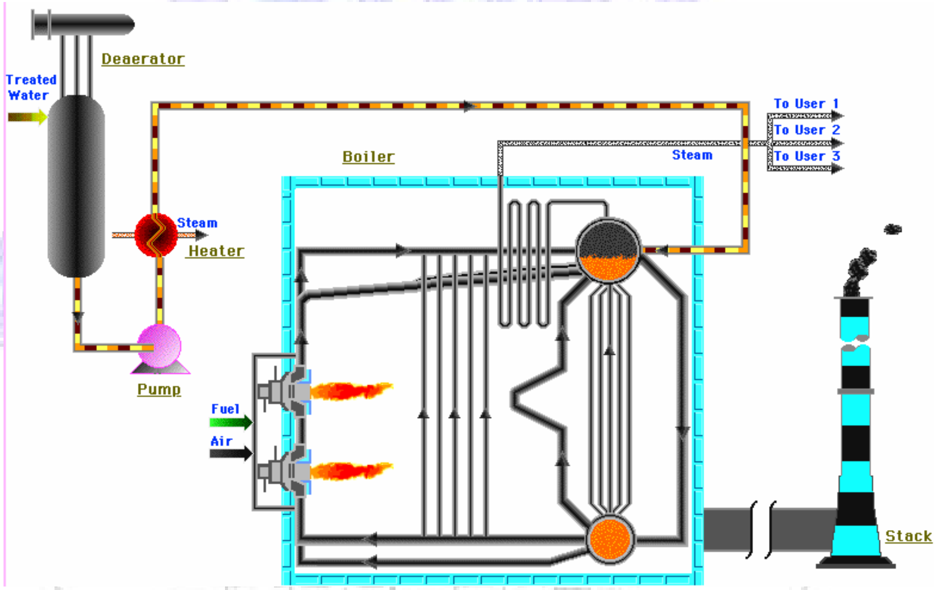

Fig. 1-1: Boiler Schematic

The Boiler Feed Water (BFW) is first demineralized and then introduced into the boiler. The energy required for the steam generation is obtained by burning fuel oil or fuel gas with air. The hot combustion gases also known as flue gas transfer heat by radiation and convection to the water to generate steam. The cold flue gas leaves the boiler through the stack and is discharged into the atmosphere.

The steam produced in a boiler is used in various equipment in a plant and hence the boiler operation directly affects the overall plant performance. If a boiler shuts down a significant portion of the plant may have to be shut down.

The fuel used in the boiler is highly combustible and any mishandling of the fuel can lead to hazardous conditions. For better plant performance and safety, an operator must have a sound knowledge of a boiler's components and its operating principles.

1.2 Applications of Boilers

Various equipment in refinery and petrochemical plants require steam at various pressure levels. Normally, three levels of pressurized steam are used, namely

- High Pressure Steam,
- Medium Pressure Steam and
- Low Pressure Steam.

In a boiler the steam is generated at high pressure, hence it is called High Pressure (HP) steam. A part of the HP steam is let down to make Medium Pressure (MP) steam and then further let down to make Low Pressure (LP) steam.

In a plant the steam system has many applications, such as

- Stripping steam for distillation columns,
- Motive steam for turbine drivers,
- Heating fluid for heat exchangers,
- Atomizers for liquid fuels

and so on.

In some processes steam is also used as a major reactant or as a promoter in reactors such as steam reformers in the production of synthesis gas and steam cracking in the production of ethylene.

Some boilers are specifically designed to drive generators to produce electric power. Such boilers are called *co-generation boilers* or *power boilers*.

1.3 Types of boilers

There are several types of boilers and their structure varies widely depending on their capacity. Boilers can be classsified on

- Mode of the water flow and
- Mode of Air and Flue Gas flow.

- Classification based upon water flow

  In boiler the water can be heated in many ways. In some boilers the water converts to steam as it flows from inlet to outlet in heating tubes. This type of boilers is called *once-through boiler* and it is normally operated in the supercritical pressure region. It is mainly used for large capacity power plants.

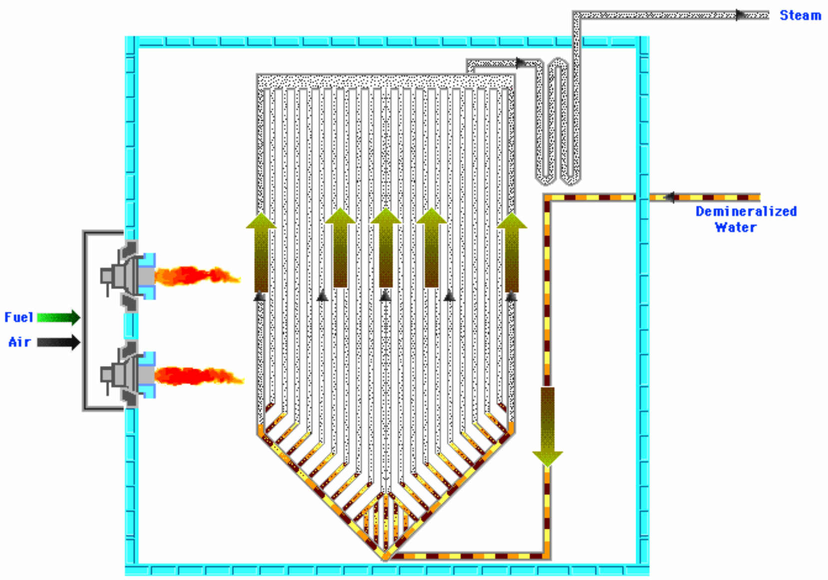

Fig. 1-2: Once-through Boiler

In another kind of boiler the flue gas flows through the boiler tubes which are submerged in the water. The steam is generated by transferring heat from the hot flue gas in the tubes to the water on the shell side. This type of boiler is called a *firetube boiler* and it is used for small to medium sized industrial boilers.

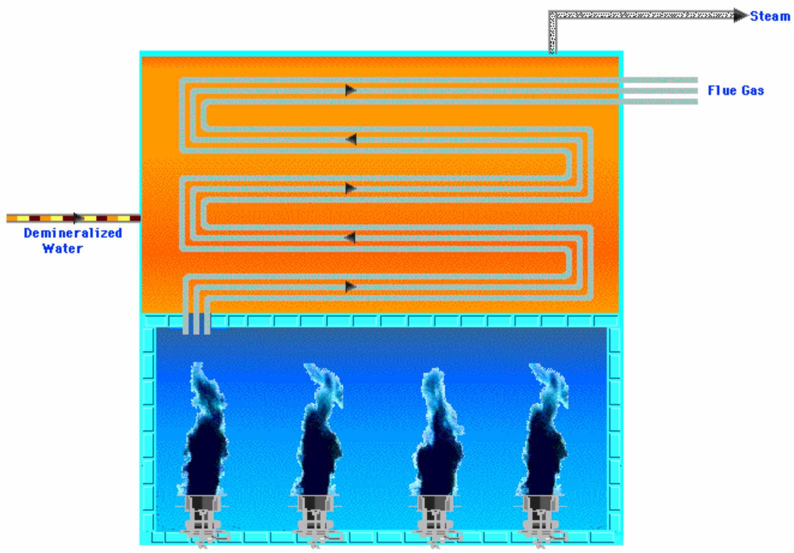

Fig. 1-3: Fire-tube Boiler

The most commonly used boiler is called a *drum-type boiler*. In this boiler the water enters a drum and then circulates through the heating tubes to produce steam. The steam from the drum is further heated to higher temperatures by the hot flue gas.

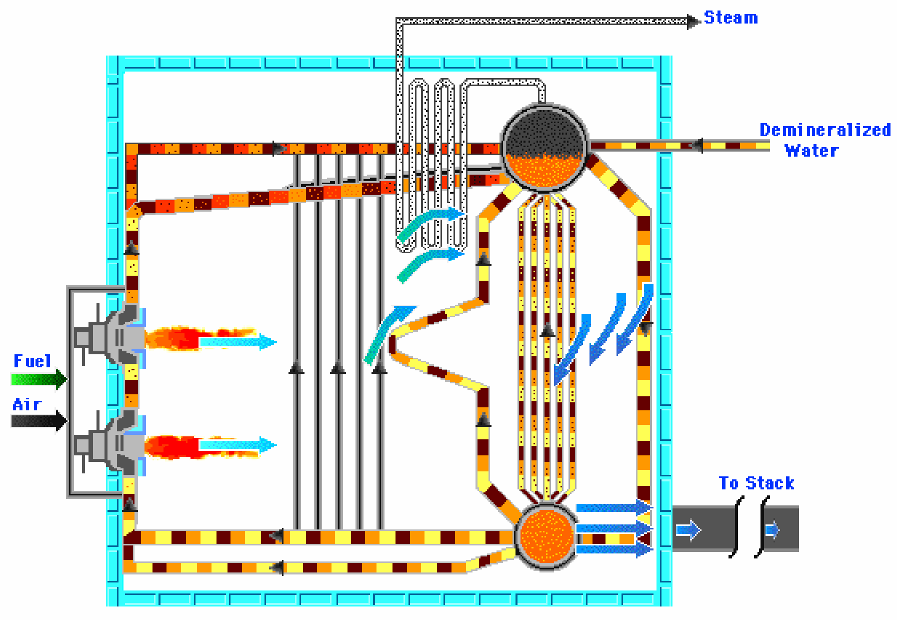

Fig. 1-4: Drum-type Boiler

- Classification based upon air and flue gas flow

There are two main types of air and flue gas flow systems:

- Natural-draft system
- Forced-draft system.

In a natural-draft system as the hot flue gas flows through the stack the air required for the combustion flows into the boiler firebox due to a phenomenon called *natural convection* and does not require any fan or blower.

In a forced-draft system an external mechanical force provided by a fan or blower is used to circulate air and flue gas. There are three types of a forced-draft system.

In one system the air is forced into the boiler firebox with help of a fan located upstream of the burner. This type of a boiler is known as a *forced-draft boiler*.

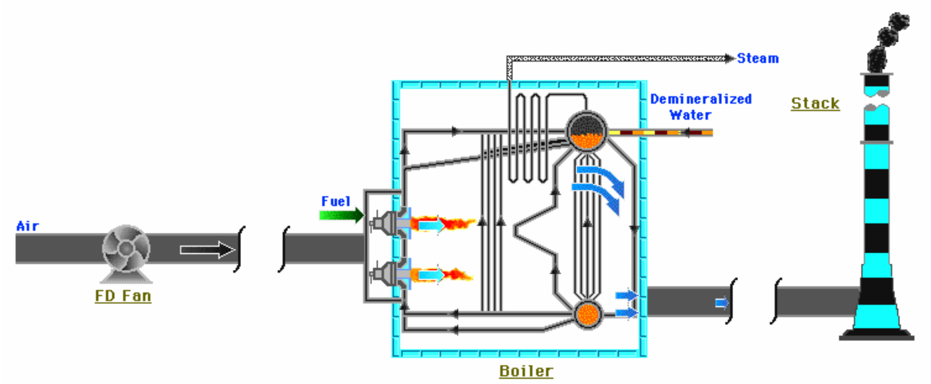

Fig. 1-5: Forced-draft Boiler

In a second system a fan located downstream of the boiler which draws hot gas from the boiler. This generates negative pressure in the firebox and sucks in atmospheric air. This type of boiler is known as an ***induced-draft boiler***.

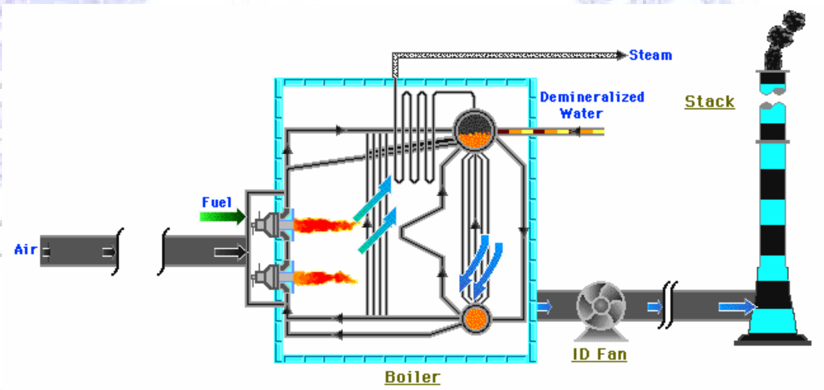

Fig. 1-6: Induced-draft Boiler

The third system utilizes two fans simultaneously. One for forcing air into the boiler and the other for withdrawing the hot flue gas out of the boiler. This type of a boiler is known as a ***balanced-draft boiler***. It is mainly used for high capacity power plants.

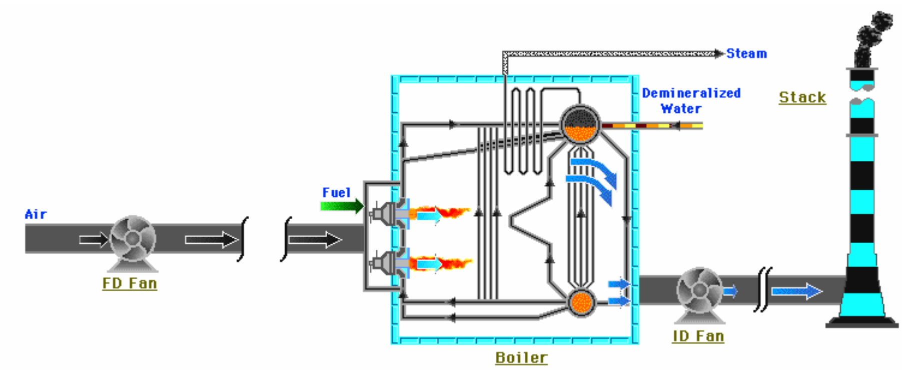

Fig. 1-7: Balanced-draft Boiler

This course focuses on a forced-draft drum type boiler as it is used most commonly in process industries.

2 Boiler Components

2.1 Introduction

Let us analyze broadly how the water is converted into steam in a boiler. The chemically treated feed water first enters a *Deaerator* where the trapped air in the water is stripped off by steam. The deaerated feed water is pumped through a feed water heater and then sent to a drum located at the top of the boiler called the *Steam Drum*. The water from the steam drum flows down through a *Downcomer* and enters another drum at the bottom of the boiler called *Mud Drum*. From the Mud Drum the water flows up through *Heating Tubes* back into the Steam Drum.

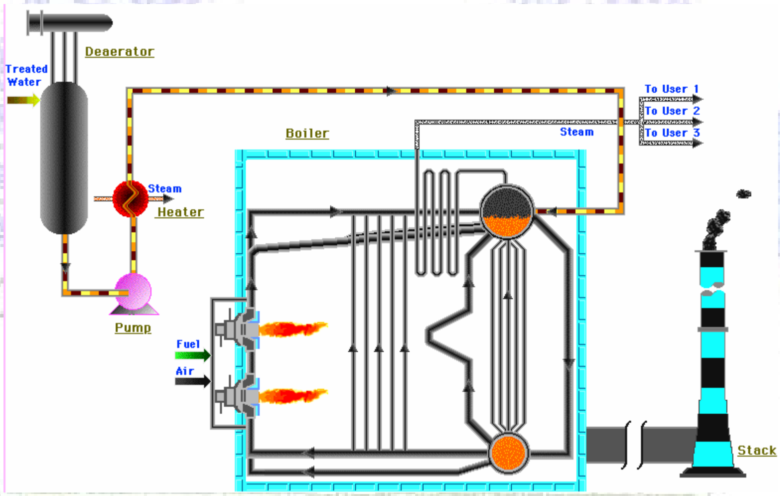

Fig. 2-1: Boiler System

The fuel oil or fuel gas is burned with air in a combustion device called *Burner* to generate the heat. The hot flue gas heats the water flowing up through the Heating Tubes by *radiative* and *convective heat transfer*.

The water is partially converted to steam and returned to the Steam Drum. The steam is separated in the Steam Drum and then superheated by the hot flue gas in a *Superheater* before it is sent to the users in the plant.

The various components in a boiler can be grouped as

- Deaerator and Feedwater system,
- Water Circulation and Heating system,
- Superheater, De-Superheater and Heat Recovery system,
- Combustion system,
- Draft system and
- Steam Distribution system.

2.2 Deaerator and Feedwater system

The water normally contains tiny air bubbles. The oxygen and CO_2 in the air bubbles accelerate the corrosion of the metal used for heating tubes and drums. Therefore, the air trapped in the water must be removed before it is sent to the steam drum. A Deaerator which is normally a vertical cylinder is used.

The chemically treated water is sprayed into the Deaerator through nozzles located at the top. The water is then made to contact with the steam injected at the bottom. The air trapped in the water is stripped off by the steam and released to the atmosphere along with the steam. A portion of the steam condenses at the top of the Deaerator at a heat exchanger known as *Vent Condenser*. The condensed steam flows back into the Deaerator.

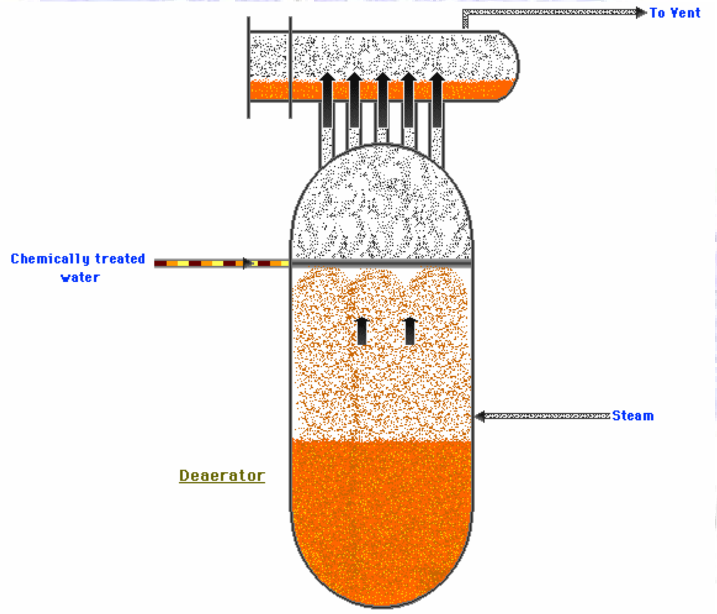

Fig. 2-2: Principle of Deaerator

The steam drum is at a higher pressure and temperature, hence the deaerated water needs to be heated and pumped into the steam drum. The water entering the steam drum is called *Feedwater*. The Feedwater pumps are used to pump the deaerated Feedwater through a *Pre-Heater* into the Steam Drum.

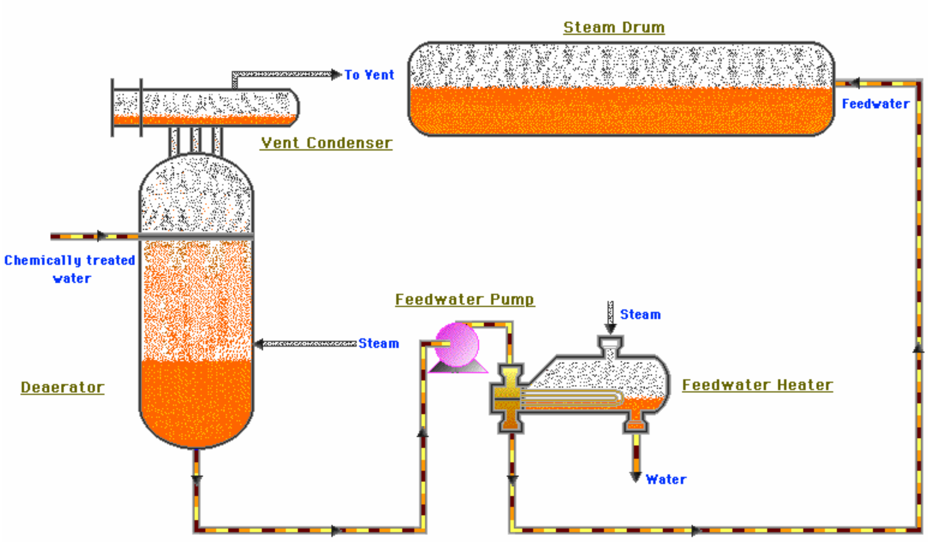

Fig. 2-3: Overview of Feedwater System

2.3 Water circulation and heating system

This section consists of

- the Steam Drum,
- the Mud Drum,
- the Downcomer and
- the Heating Tubes.

2.3.1 Steam Drum

The Steam Drum is located at a higher elevation in the boiler and is connected with the Mud Drum at a lower level with tubes. The feedwater from the deaerator enters the Steam Drum, mixes with the hot saturated water and flows down through the tubes into the Mud Drum. The water from the Mud Drum circulates back to the Steam Drum via various heating tubes where the water is partially converted to steam. In the Steam Drum the steam is separated from the returning water steam mixture. A baffle is placed near the return nozzles to enhance this separation. This steam is in equilibrium with water and is called *saturated steam*. The saturated steam leaves the drum for further heating. Sometimes the water droplets get carried away with the steam and they damage the downstream equipment. Normally a screen-like steam-water separator is installed near the steam exit to remove the water droplets.

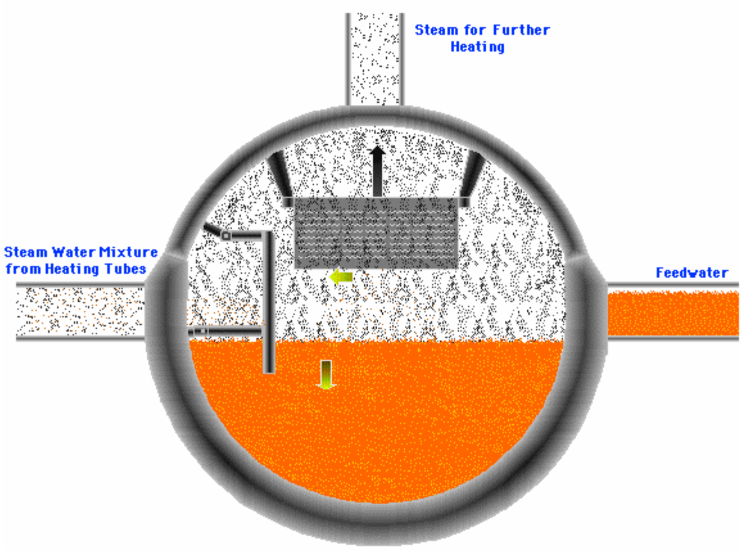

Fig. 2-4: Cross-section of Steam Drum

Although the feedwater is well treated before it enters the Steam Drum some minute amounts of inorganic compounds still exist and they eventually deposit as solids in the drum. These deposits will continue to accumulate in the Steam Drum unless they are removed. A small portion of the water from the Steam Drum is drained regularly to eliminate accumulation of solid deposits. This withdrawal of water is called ***Blowdown***. Normally, the Blowdown operation from the Steam Drum is continuous.

2.3.2 Water circulation and heating tubes

The feedwater after mixing with the saturated water in the steam drum flows down through the tubes called *Downcomer*. The Downcomer tubes are connected to a smaller drum located at the bottom of the boiler called the *Mud Drum*. The Downcomer tubes are not exposed to the burner heat. Hence, very little heating takes place. The water from the Mud Drum flows up to the Steam Drum via various *Heating tubes*. The Heating tubes are exposed to intense heat from burner flames and hot flue gas. A portion of the water evaporates to become steam and the resulting steam-water mixture returns to the Steam Drum.

In most drum-type boilers the boiler walls are protected from intense radiation heat with water tubes that cover the inner surfaces of the boiler walls. Many tubes are bundled together with pins to form a single heating metal piece to protect the wall. This arrangement of Heating tubes is called a *water wall*. In the water walls the water is heated mainly with *radiative heat transfer* from the hot flue gas. Some boilers have an additional *convective section* where the water is heated by *convective heat transfer* from the hot flue gas.

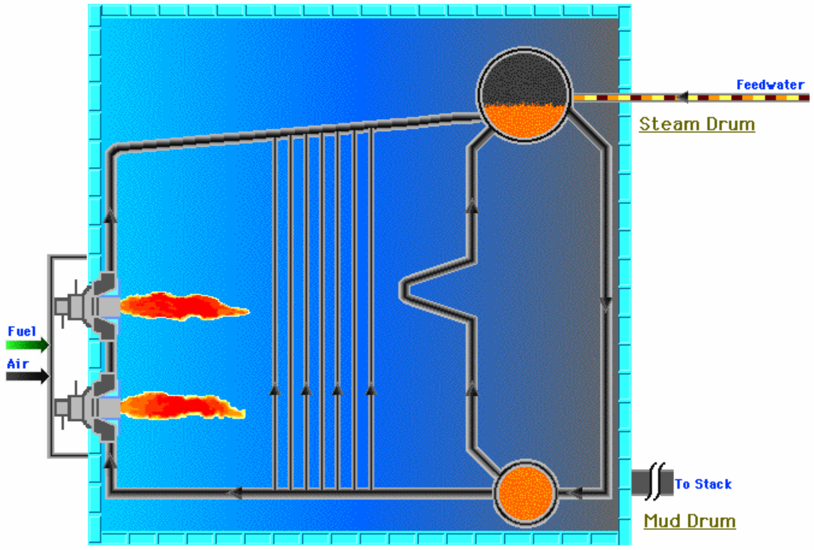

Fig. 2-5: Radiative and Convective Heat Transfer

The water circulates continuously between the Steam Drum and the Mud Drum by natural circulation. The natural circulation occurs due to the static head difference between the water in the Downcomer and the water in the Heating tubes. The density of the relatively cold water in the Downcomer is higher than that of the hot water-steam mixture in the Heating tubes. This difference in the density and the elevation between the Steam Drum and the Mud Drum causes natural water circulation. This phenomenon is called *Natural Convection*.

The function of the Mud Drum is to facilitate water circulation and remove deposits from the water. The sludge and other impurities deposit as solids and are removed by blowing down a small quantity of water. Since the blow down tends to reduce the natural circulation force for the water the blow down operation is performed intermittently for short duration.

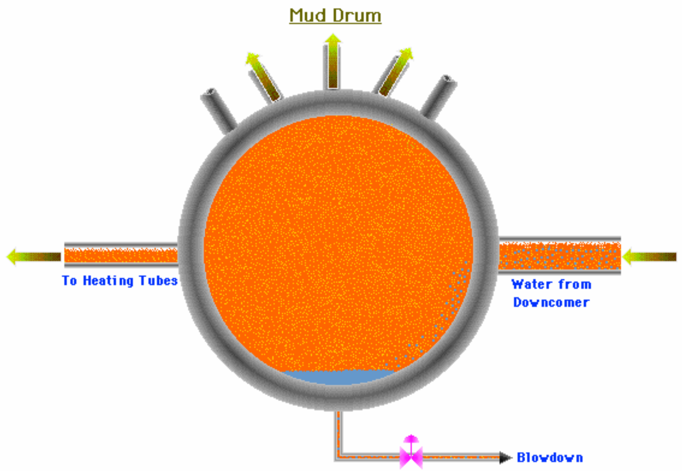

Fig. 2-6: Cross-section of Mud Drum

2.4 Superheater, De-Superheater and Heat Recovery

In the Steam Drum the steam is in equilibrium with water and it is called saturated steam. A slight cooling of this saturated steam would result in water droplet formation that may damage the down-stream equipment. Hence, the saturated steam leaving the Steam Drum is further heated in a heat exchanger called *Superheater*.

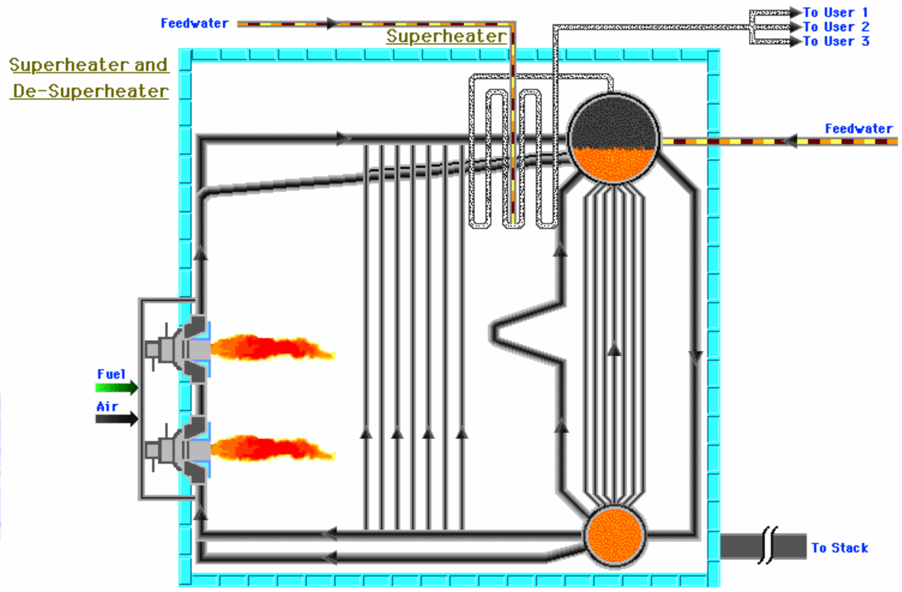

Fig. 2-7: Boiler with Steam Superheaters

Normally, there are two Superheaters, primary and secondary. The saturated steam from the Steam Drum initially enters the primary Superheater where it is heated by radiative heat transfer from the flue gas. The superheated steam enters then an equipment called *De-Superheater* where a small controlled quantity of water is injected to control the final steam temperature. Sometimes the De-Superheater is known as an *Attemperator*. After the De-Superheater the steam enters the secondary Superheater where it is further heated by the convective heat transfer from the flue gas. The resulting high temperature superheated steam leaves the boiler for distribution to the users.

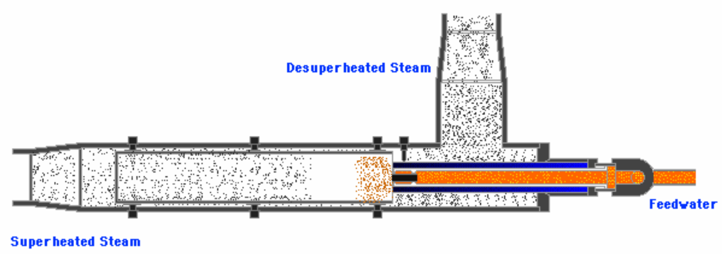

Fig. 2-8: Schematic Drawing of a Spray Attemperator

2.5 Economizer

The cold feedwater needs to be heated before it enters the steam drum. Normally it is heated with hot flue gas in a heat exchanger called *Economizer*. The Economizer is located in the recovery section of the boiler after the secondary Superheater. An Economizer provides additional heat to the feedwater and reduces the fuel requirements. The use of the Economizer increases the boiler efficiency and saves energy.

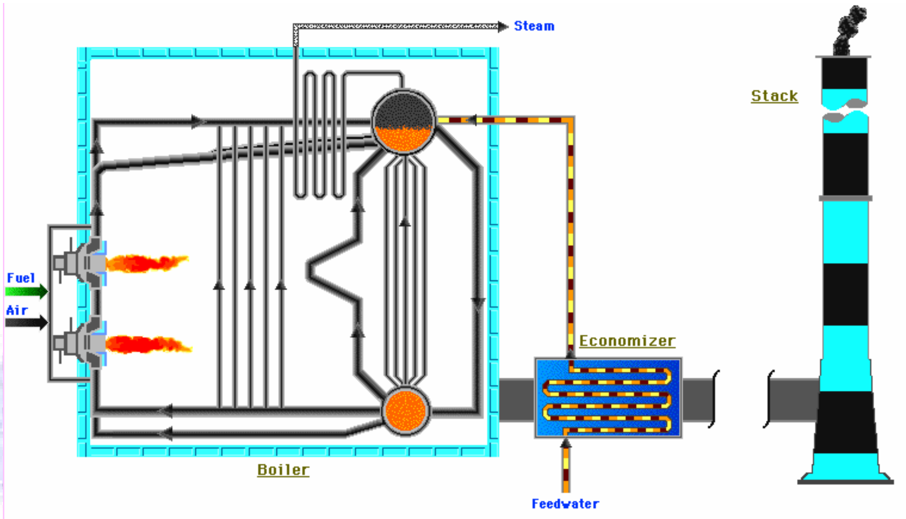

Fig. 2-9: Economizer in the Recovery Section

In some drum-type boilers the steam from the boiler is used instead of flue gas to heat the feedwater.

2.6 Combustion System

In industrial boilers fuel oil or fuel gas is used most commonly. The burners are used as combustion devices to generate heat. The boiler delivers air and fuel to the combustion chamber where it is mixed properly and then ignited to burn efficiently. Burners are normally placed vertically on the side wall to provide adequate heating to the heating tubes. Typically, four burners are used for industrial boilers. The area where the burners are located inside the boiler is surrounded with flames and hence it is called the *firebox*. In a burner the air required for the combustion is inspirated and is known as *primary air*. In some burner additional air, called *secondary air*, is also supplied in a typical burner for secondary combustion of any unburnt fuel. The primary and secondary air flows can be adjusted using *air registers* to provide a stable flame and an efficient combustion.

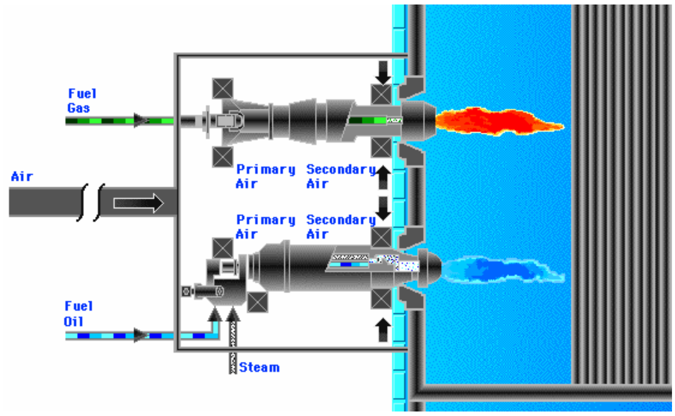

Fig. 2-10: Schematic Drawing of Burners

Burners are classified into three categories based on the type of fuel used:

- Gas Burners are used for gaseous fuel,
- Oil Burners are used for liquid fuel and
- Combination Oil and Gas Burners are used for simultaneous use of liquid and gaseous fuel.

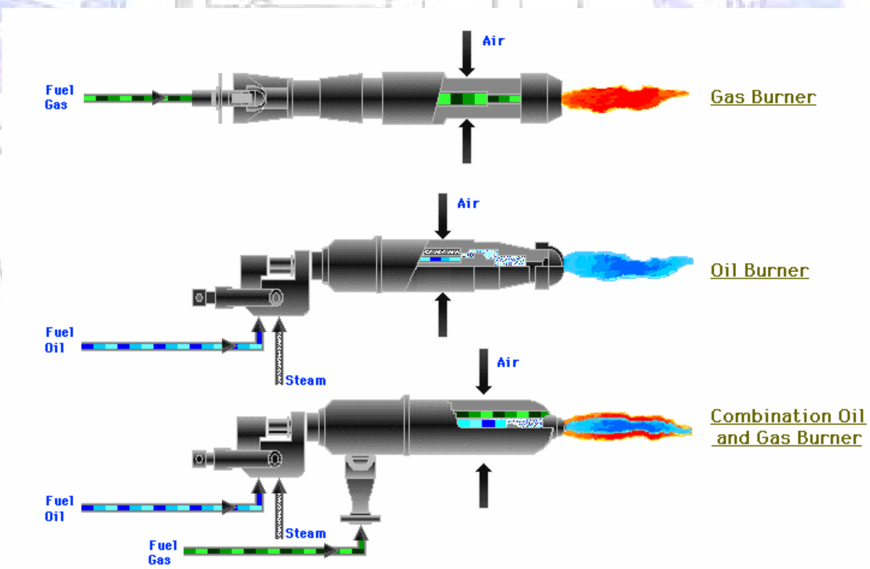

Fig. 2-11: Schematic Drawing of different Burner Types

2.6.1 Gas Burner

There are two basic categories of gas burners:

- A raw gas burner and
- A pre-mixed burner.

In a raw gas burner gaseous fuel enters the firebox directly and mixes with the secondary air. No primary air is used for this burner.

In a pre-mixed burner the gas flows through a narrow nozzle and inspirates combustion air prior to ignition at the burner tip. There are again two types of pre-mixed burners:

In one type the entire combustion air is inspirated at the nozzle. In the other type the gaseous fuel is first mixed with the inspirated primary air at the nozzle and is further mixed with secondary air just before the combustion point.

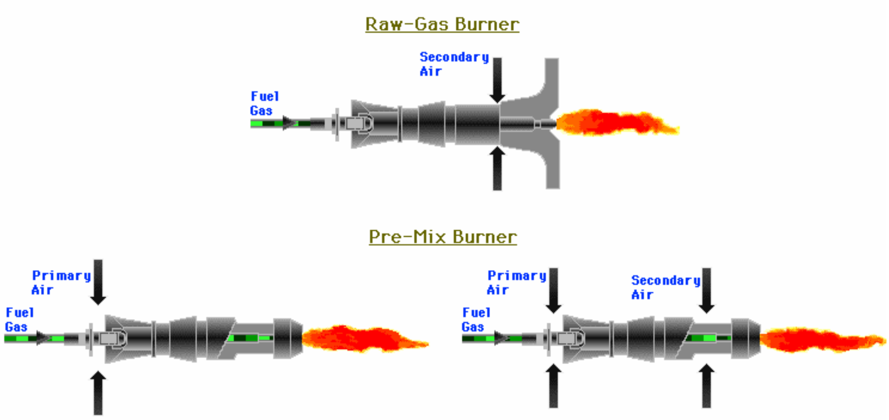

Fig. 2-12: Commomly used Gas Burners

2.6.2 Oil Burner

The oil burner has a co-axial tube through which the fuel oil is injected. For efficient combustion the fuel oil needs to be broken into a fine mist. The process of converting fuel oil into a fine mist is called *atomization*. Among the various fuel oil atomization techniques the *steam atomization* is used most commonly. In this the oil flows through the inner tube and the atomizing steam flows through the outter tube at a higher pressure. The steam mixes with the oil and also atomizes the oil. The atomized oil is injected radially, mixed with the air and then burnt. Both primary and secondary air are used for the combustion and are mixed with the fuel oil before the combustion point. The adjustment of air flow to the burner is similar to the gas burner.

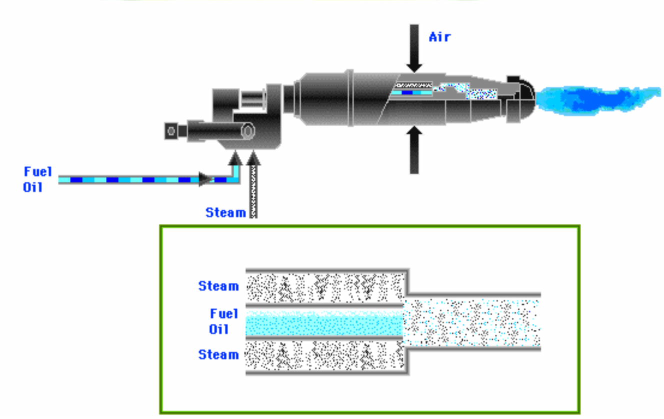

Fig. 2-13: Principle of Fuel Atomization

2.6.3 Combination Oil and Gas Burner

The combination oil and gas burner can be operated with fuel gas alone or fuel oil alone or with both oil and gas. It consists of a oil burner in the center surrounded by four to twelve gas burners.

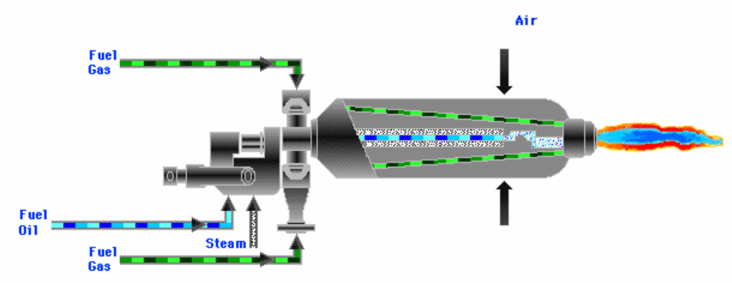

Fig. 2-14: Principle of Combination Oil and Gas Burner

2.6.4 Pilot Gas Burner

A small gas burner called Pilot Gas Burner is used to provide ignition for the main burners. The pilot gas burners is initially lit with a device called *ignitor*. An ignitor is normally electronic and it produces a spark to light the pilot burner.

2.7 Draft System

The air is supplied to the burners and the resulting flue gas leaves the boiler through the stack. This flow of the gases takes places due to the pressure difference between the heating section in the boiler and the atmosphere. This pressure difference is called *Draft*. The Draft is controlled by adjusting the dampers in the air or flue gas flow docks.

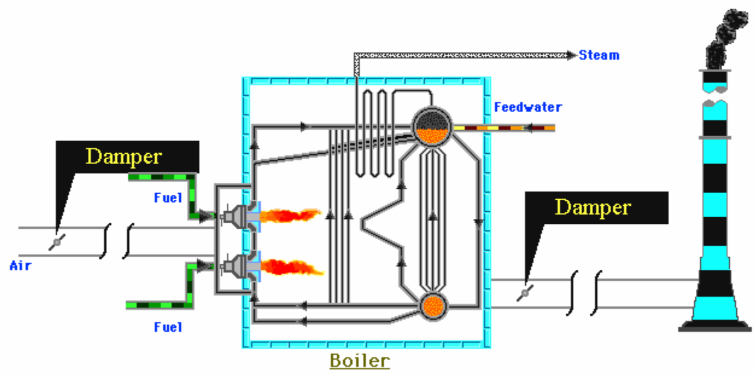

Fig. 2-15: Controlling the Draft with Dampers

A boiler in which the air is supplied by natural air convection is called a *natural draft boiler*. In this type of boilers the air registers of the individual burners are used to control the combustion air flow.

A boiler in which the air is supplied by fan is called a *forced draft boiler*. The total combustion air flow to the boiler is controlled by adjusting the vane opening of the forced-draft fan. In a forced draft boiler the combustion air is first heated in an exchanger known as *air heater*. The air heater is located in the recovery section of the boiler and it uses the exit flue gas for heating. A type of air heater known as *regenerative air heater* is used most commonly. This heater has several compartments with heat storage elements that rotate around a shaft. The hot flue gas passes through one side of the heater and heat the rotating storage elements. The cold air passes through the other side and picks up the heat from the rotating elements. In some boilers a steam heater is used to heat the air.

2.8 Steam Distribution System

In a plant various equipment requires steam at different pressure levels namely high, medium and low pressures. The steam generated by the boiler is called high pressure (HP) steam. It is sent to a header called high pressure steam header or simply *HP header*. The steam from the HP header is used by high pressure steam users in the plant.

Medium pressure steam is generated by the discharge of high pressure steam users or by letting down some high pressure steam to the medium pressure steam header also known as *MP header*. The MP steam temperature is controlled with a De-Superheater located after the HP letdown valve.

Low pressure steam is generated by the discharge of high pressure and medium pressure steam users or by letting down some of the medium pressure steam to a low pressure steam header also known as *LP header*. The LP steam temperature is controlled with a De-Superheater located after the MP letdown valve.

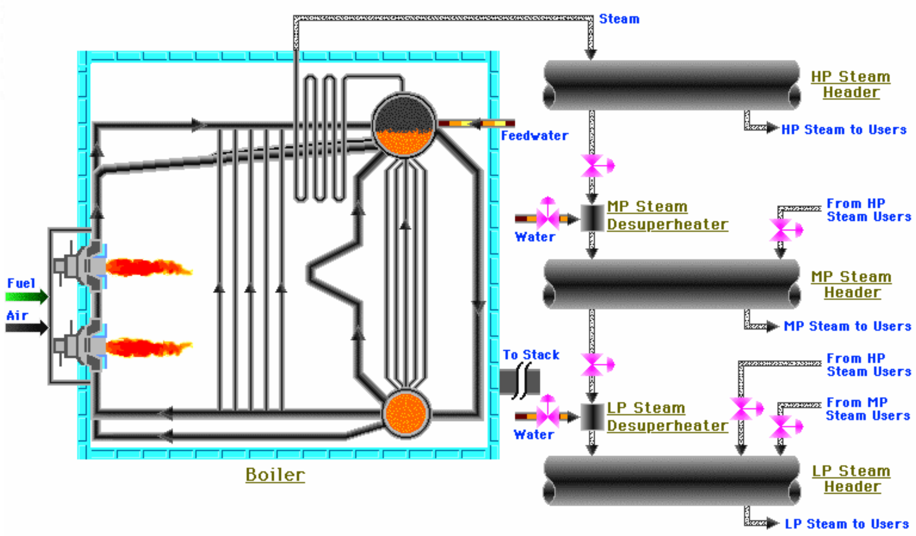

Fig. 2-16: HP, MP and LP Steam Headers

The high pressure steam is used to drive rotational equipment such as turbines. A steam turbine that uses high pressure steam normally discharges at medium or low pressure. This exhaust steam is returned to MP or LP steam headers for further distribution.

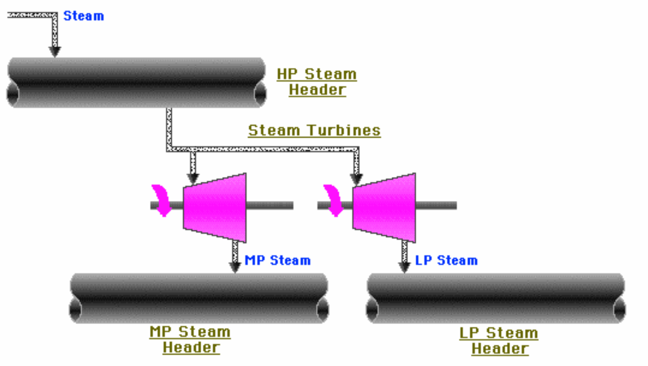

Fig. 2-17: Usage of HP Steam

The medium pressure steam is normally used in towers as stripping steam, to heat process fluids, to atomize liquid fuels or create vacuum in ejectors and so on.

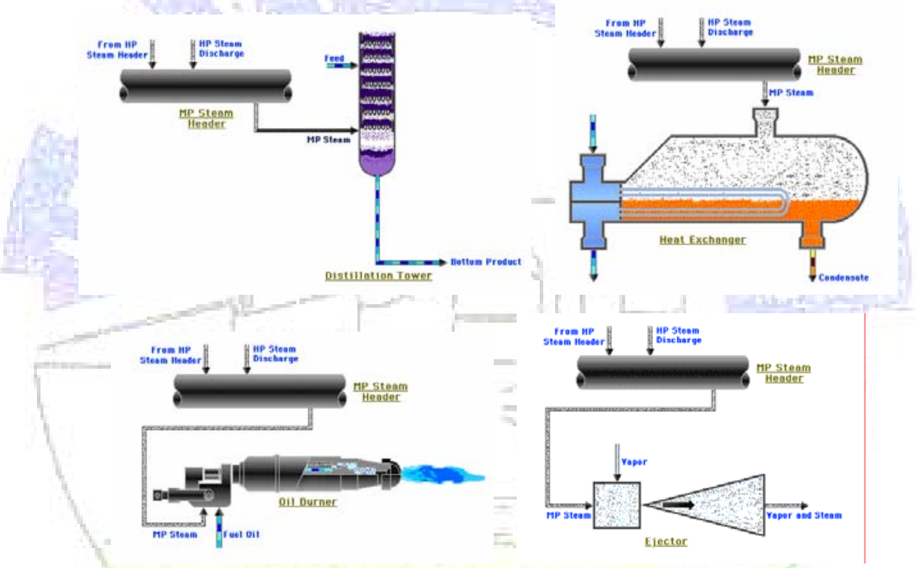

Fig. 2-18. Usage of MP Steam

The low pressure steam is normally used as stripping steam and in reboilers of distillation columns. It is also used to heat process fluids, to purge process vessels, to regenerate catalyst beds in reactors and so on.

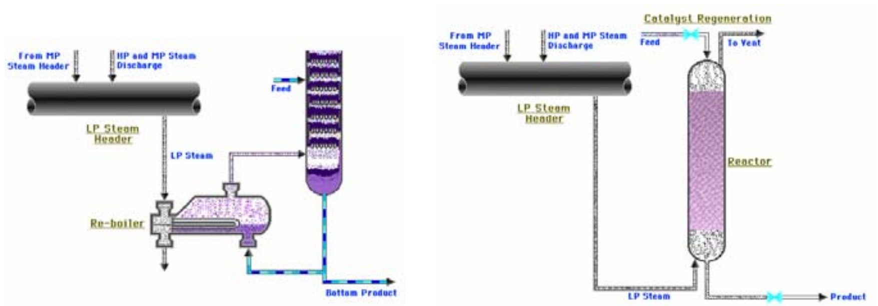

Fig. 2-19: Usage of LP Steam

In a co-generation boiler the steam generated by the boiler is used to drive the steam turbine for the generator. The extracted and exhausted steam from the turbine are further used as medium or low pressure steam respectively.

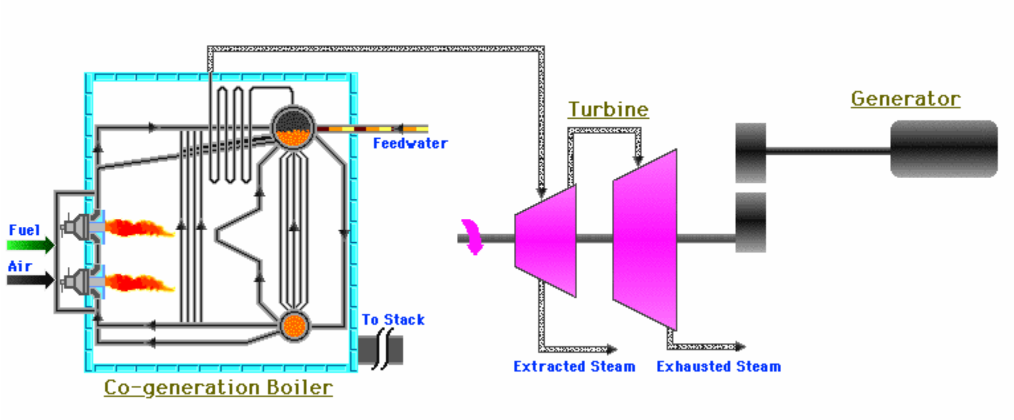

Fig. 2-20: Usage of Steam for Power Generation

3 Boiler Performance

Boilers form an integral part of many process plants. When a boiler is shut down the effect on the entire plant is substantial resulting in huge loss of the operating revenue. The boiler fuel represents a significant portion of the total operating cost. Hence, an efficient fuel management is desirable as it leads to substantial savings. The fuels used in the boiler are highly combustible and their handling is very critical from the safety point of view. The boiler also handles high pressure and high temperature fluids and it has potential safety hazards. Hence, it is essential to understand various performance and safety related issues for a safe and efficient operation.

3.1 Burner Characteristics

Every burner has a characteristic curve that relates the combustion rate to the number of burners required. For each burner there exists a maximum and a minimum limit on the combustion rate for the fuel flow rate for sustaining a stable flame. Once the combustion rate goes beyond these limits the burner cannot sustain a stable flame and this can lead to a *flame-out*. A flame-out results in accumulation of unburnt fuel in the boiler and is a fire hazard.

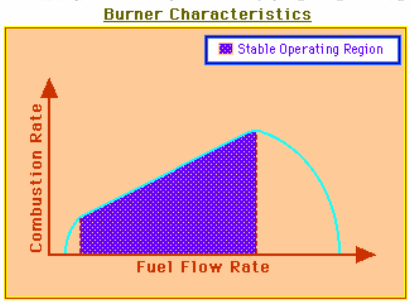

Fig. 3-1: Characteristic Curve

In a gas burner the stable operating range is determined by the fuel gas pressure at the burner inlet. In an oil burner the stable operating range is determined by the fuel oil pressure and the atomizing steam pressure at the burner inlet.

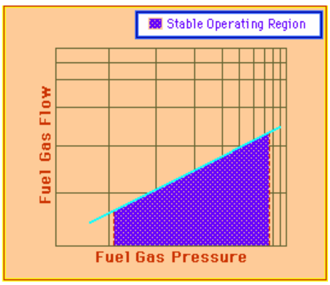

Fig. 3-2: Gas Burner Characteristic

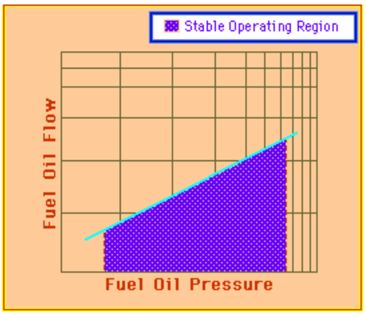

Fig. 3-3: Oil Burner Characteristic

For example, during start-up when an additional burner is fired the fuel flow rate for the first burner decreases. Hence, the fuel pressure of the burner already in service may decrease below its stable operating range. This may lead to an unstable flame or flame-out. To avoid this situation the fuel pressure at the burner already in service may have to be adjusted before lighting the additional burner.

Usually, the number of burners required for the boiler operation is determined using the following guidelines:

- Calculate the total heat requirement
- Calculate the total fuel flow from the total heat requirement
- Calculate the number of burners required from the burner characteristic curves

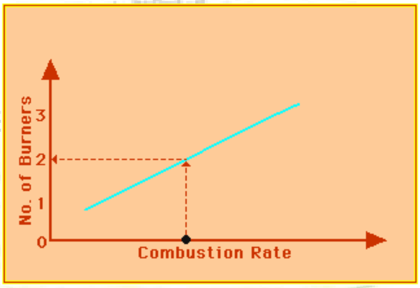

Fig. 3-4: Combined Burner Characteristic

3.2 Combustion Air

It is essential to supply an adequate amount of air for complete combustion of the fuel. Insufficient air flow leads to <u>*partial combustion*</u> of fuel and the partially burnt fuel escapes with the flue gas. This results in a loss of fuel and poses a safety hazard. On the other hand, <u>*excess air*</u> can be supplied to the burner for complete combustion. But high excess air increases the total air and flue gas flow and reduces the temperature in the firebox. This leads to a reduction of radiative heat transfer in the heating tubes. As a result, the flue gas temperature in the superheater and the heat recovery sections increases. With higher flue gas temperature at the boiler exit more heat is lost to the atmosphere via the stack. Hence, providing the optimal amount of air is very important. Please note that the heat loss by the exit flue gas is due to unutilized or unrecoverable energy and is also known as *stack loss*.

The carbon in a hydrocarbon fuel upon combustion with oxygen is first converted to carbon monoxide. The carbon monoxide further burns with oxygen to form carbon dioxide. Both these reactions generate heat. In case of inadequate air the second reaction may not complete fully. This is *called partial combustion*. Due to partial combustion the combustion heat is lower and a high level of carbon monoxide is present in the flue gas.

The minimum amount of stochiometric air required for the complete combustion of fuel is called the *theoretical air*. In practice, due to the burner inefficiencies, like improper mixing of fuel and air, complete combustion cannot be achieved with just the theoretical air. Hence, a certain amount of *excess air* is supplied to ensure complete combustion of the fuel. Excess Air is defined as the difference between the amount of air supplied and the theoretical air. Excess air equals

$$F_{Ex} = F - F_T$$

where F is the amount of air supplied and F_T is the theoretical air. The percent ratio of excess air to the theoretical air is called the *excess air ratio*. It is often used to indicate the amount of excess air supplied. Excess air ratio equals

$$R_{Ex} = 100 * (F - F_T) / F_T$$

For most economical burner operation a complete combustion of the fuel with minimal excess air ratio should be achieved. The optimal excess air ratio varies widely with the extent of mixing of air and fuel and the fuel type. The extent of mixing depends on the type of the fuel and the burner structure. Generally, 5 to 30% of excess air is used in gas burner and 15 to 30% of excess air is used in an oil burner.

In modern boilers the excess air in the flue gas is measured and automatically controlled using some advanced control strategy. Please note that some minor quantity of air always leaks in the boiler with the result the O_2 measurement in the boiler is always higher than the actual O_2 at the burner. Hence, excess O_2 measured at the analyzer is not a proper indication of O_2 availability at the burners. In case of incomplete combustion all fuels produce CO and traces of hydrocarbons. Hence, CO and hydrocarbon analyzers are also installed to monitor and control boiler performance.

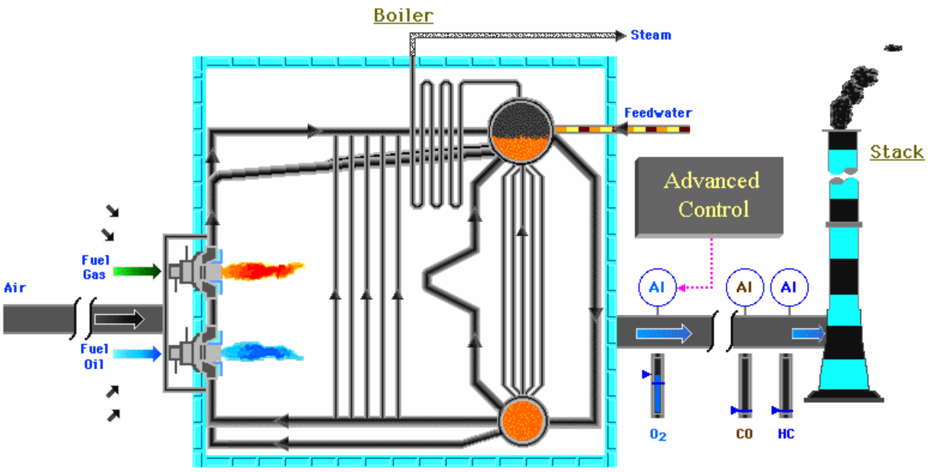

Fig. 3-5: Control of Excess Air

3.3 Damper and Air Registers

Dampers, vanes and air registers are used to control the air supply and the draft in a boiler. In a forced-draft boiler the total air flow rate is controlled by either a *damper* or by the *vanes* of the forced-draft fan. The dampers in the air circuit and the flue gas circuit are used to adjust the boiler draft.

In a natural draft boiler the air registers are used to control the air flow at individual burners, while in a forced-draft boiler the air registers are used only for fine adjustment of air flow at each burner. The effect of mixing of air on combustion can be observed by inspecting the burner flame condition. The flame condition is observed by visual inspection of flame colour, lenght, stability and the extent of lift-off from the burner tip.

3.4 Fuel Characteristics

There are various types of grades of fuel oil and fuel gas. They have different chemical compositions and their heating value varies. Hence, the amount of the fuel and the air required varies with fuel type and its composition.

For fuel oil the oil viscosity effects the flame stability and the burner performance. The effect of viscosity can be overcome by adjusting the fuel oil temperature. A higher viscous fuel oil requires a higher fuel oil temperature for stable flame. The steam and fuel oil pressure at the burner inlet effect the atomization and hence the burner performance. For a stable sustained oil flame the steam and the oil pressure should be maintained within a stable operating range. It is done by adjusting the associated regulating valves at the burner inlet. In some burners the pressure difference between the atomizing steam and the oil supply lines is also controlled using automatic controls.

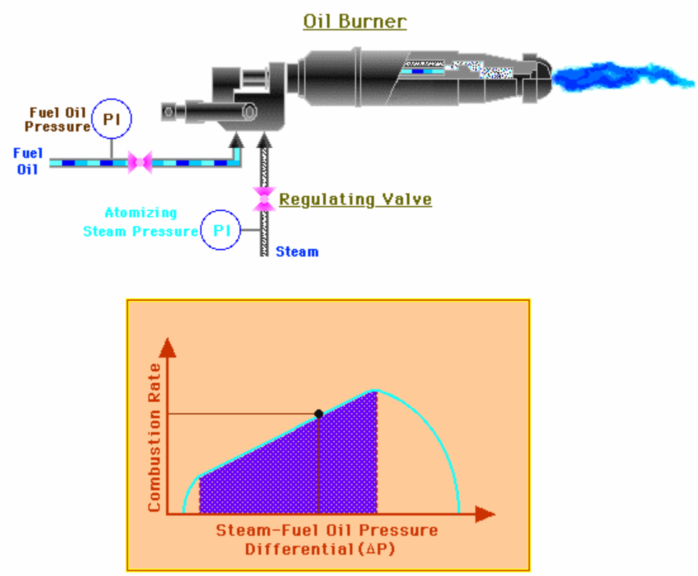

Fig. 3-6: Effect of Steam-Fuel Oil Pressure Differential on Burner Condition

4 Boiler Control System

A boiler system incorporates a number of unique control strategies. The basic objectives of the control strategy are

- to supply a continous supply of steam at the desired condition,
- to perform normal and emergency operations safely at all times,
- to continously operate the boiler with the maximum possible efficiency,
- to maintain a high level of safety and
- sustain full boiler design life.

4.1 Three-element Feed Water Control

The dynamics of a steam drum level are different than that of conventional drum and tank levels. This is due to a phenomenon known as *shrink and swell*. To illustrate the shrink and swell effect in a steam drum let us consider a sharp increase of steam consumption. With the sudden increase in the steam consumption the steam drum pressure drops immediately. With the sudden drop in the pressure the steam bubbles in the water wall and the drum swell and results in a sharp momentary increase in the drum level. After the pressure stabilizes the drum levels behaves in a conventional manner. This initial increase in the level is called *swell* and it is unique to the steam drum.

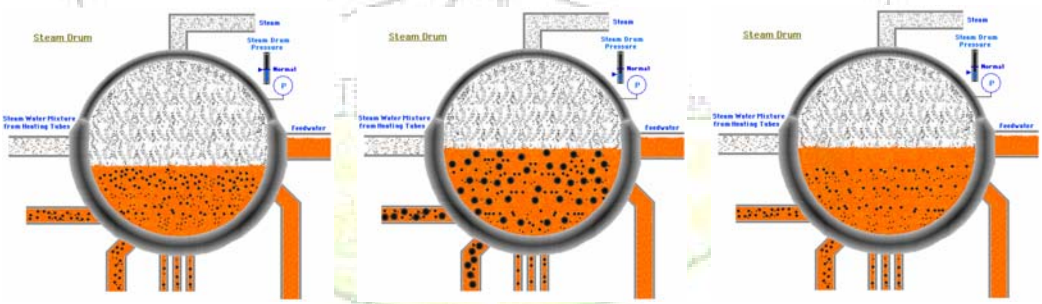

Fig. 4-1: Swell Effect after Increase in Steam Demand

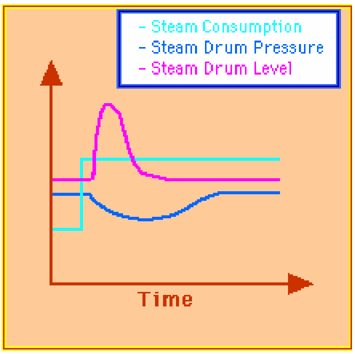

Fig. 4-2: Courses of Steam Drum Pressure and Level after Increase of Steam Demand

Similarly, when the steam consumption reduces suddenly, the drum pressure rises immediately and the steam bubbles in the water shrink. This leads to a sharp momentary decrease in the drum level. This initial decrease in the steam drum level is called *shrink*.

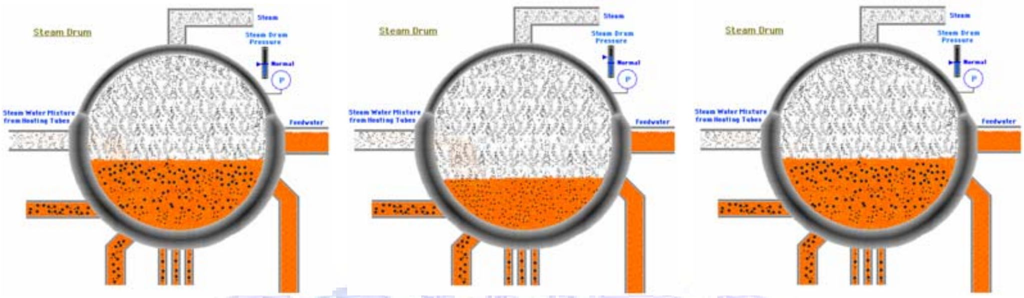

Fig. 4-3: Shrink Effect after Decrease in Steam Demand

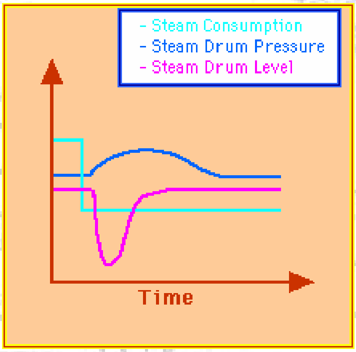

Fig. 4-4: Courses of Steam Drum Pressure and Level after Increase of Steam Demand

In a conventional two-element control strategy the output of a level controller cascades into a flow controller.

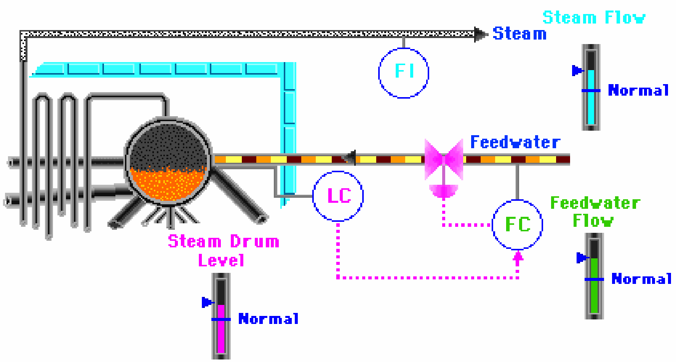

Fig. 4-5. Conventional Level Control

Let us now consider the use of a conventional two-element control strategy to control the steam drum level. As the drum level increases the controller reduces the feed water supply. And similarly, if the drum level decreases the controller increases the feed water supply. Let us assume that the steam consumption increases suddenly. Due to the swelling effect the steam drum level will rise initially and then decrease. The controller will initially reduce the feed water supply. This will in effect reduce the water inventory and after the swell effect the water drum level will drum significantly.

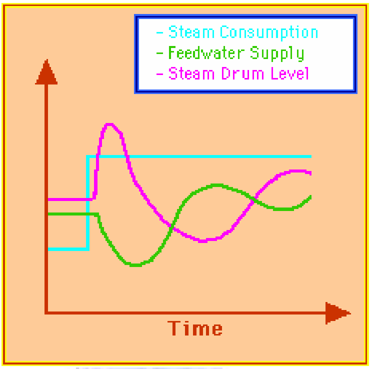

Fig. 4-6: Control Behaviour of Conventional Level Control after Increase in Steam Demand

In order to handle this situation the steam flow rate should also be considered for drum level control. It can be done by adding the steam flow rate as a feedforward signal to the output of the level controller. Hence, the supply of the feed water flow is compensated for changes in the steam flow rate demand. With this strategy as the steam flow rate changes the demand for the feed water flow rate also changes in the right direction and minimizes the effect of shrink and swell on the drum level. This control strategy is called *three-element level control*.

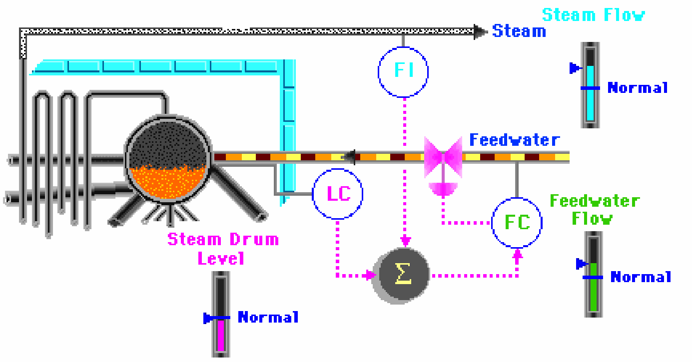

Fig. 4-7: Three-element Level Control

Now, let us assume that the steam consumption increases suddenly. As the steam consumption increases the feedforward signal increases the feed water supply to the steam drum. Due to the swell effect the level controller reduces the feed water supply. The net effect of the three-element level control scheme changes the feed water supply appropriately and reduces the effect of swell on the drum level. Thus, the three-element level control strategy provides a more stable drum level control.

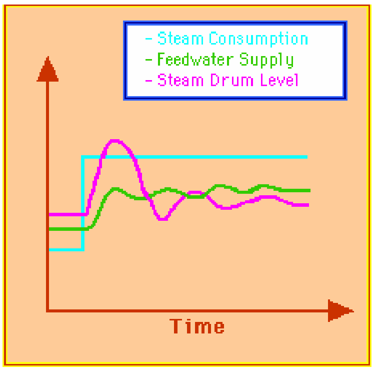

Fig. 4-8: Control Behaviour of Three-element Level Control after Increase in Steam Demand

4.2 Steam Temperature Control

The temperature of the steam leaving the boiler continuously varies with the boiler load. The main objective of the main steam temperature controller is to maintain a constant steam temperature at all boiler loads. As we know, the steam leaving the steam drum initially enters the primary superheater, then a de-superheater and finally leaves the boiler through a secondary superheater. The boiler feedwater is sprayed into the de-superheater for controling the main steam temperature. The main steam temperature controller manipulates the amount of boiler feedwater sprayed into the de-superheater to control the steam temperature. For example, when the temperature of the steam leaving the secondary superheater is high, the main steam temperature controller sprays more water into the de-superheater to maintain the temperature at the desired value.

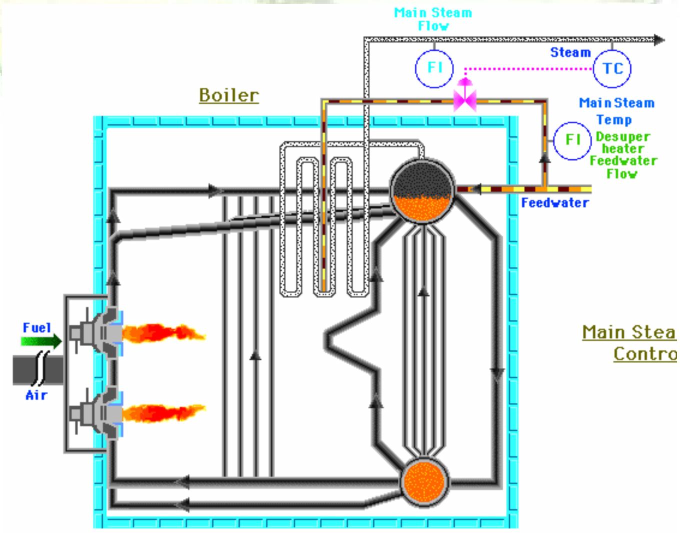

Fig. 4-9: Steam Temperature Control

Sometimes the air flow signal is provided as a feedforward signal to the output of the main steam temperature controller. With this strategy as the boiler load changes, the air flow rate also changes and the main steam temperature controller takes immediate corrective action without waiting the steam temperature to change.

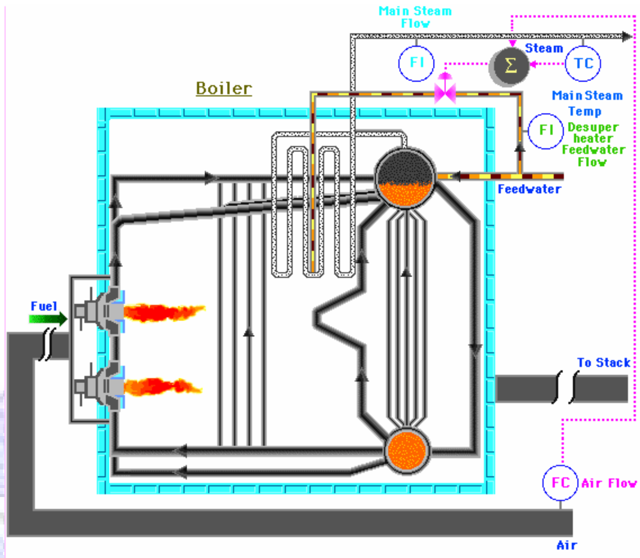

Fig. 4-10: Steam Temperature Control with Air Flow Signal as Feed forward

4.3 Steam Pressure Control

The steam pressure is subjected to contiuous changes due to continuous variations in the boiler load. As the steam demand increases the steam pressure decreases and when the steam demand decreases the steam pressure increases. Hence, the main objective of the boiler control strategy is to maintain the steam pressure at various steam demands. The steam pressure is controlled by manipulating the amount of fuel burnt. As the steam pressure increases the fuel flow is reduced to produce less steam and the steam pressure is brought back to the desired value. Similarly, when the steam pressure decreases the fuel flow is increased to produce more steam and the steam pressure is again brought back to the desired value.

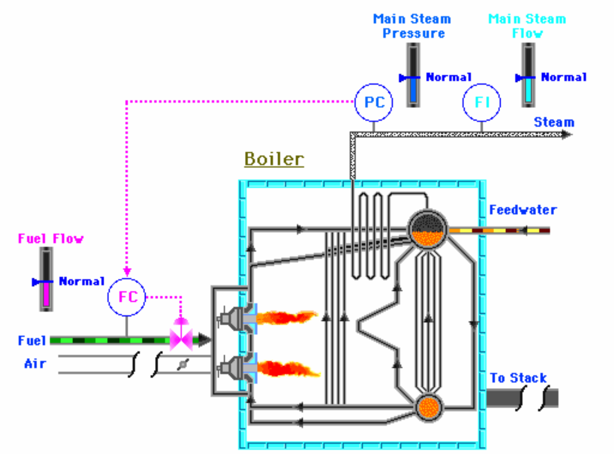

Fig. 4-11: Steam Pressure Control with Fuel Flow Control

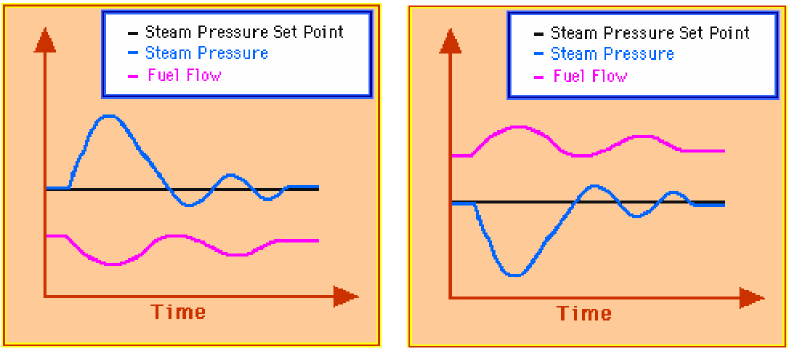

Fig. 4-12: Steam Pressure Control Behaviour

Normally, the control of the steam pressure is sluggish. This is because the size of the boiler is huge and it takes time to transfer heat from fuel firing to make steam. Moreover, the steam headers in the boiler provide stability from minor steam pressure changes. However, they provide additional lag to pressure dynamics. To overcome the sluggish behaviour the steam flow is added as a compensation signal to the output of the main steam pressure controller. This way as the steam demand changes the fuel demand changes immediately and in the right direction.

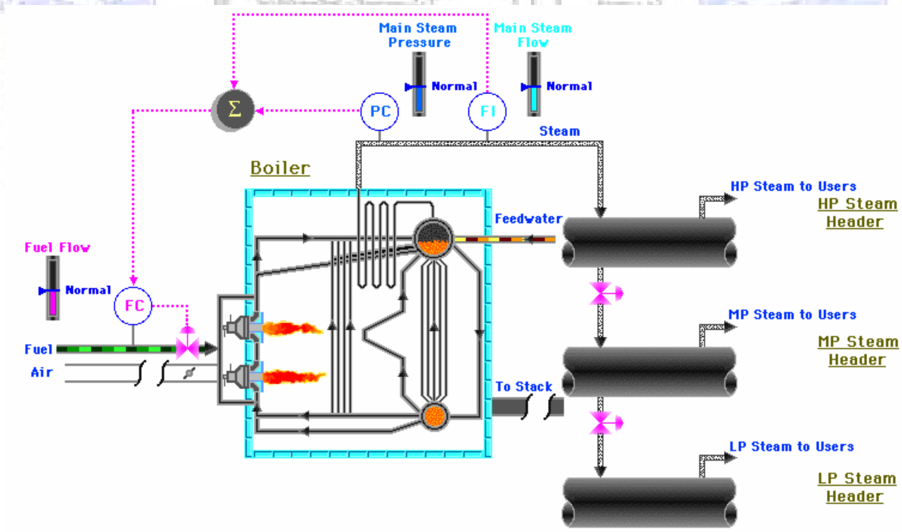

Fig. 4-13: Steam Pressure Control using Steam Flowrate as Feedforward Signal

In some boilers a separate steam flow controller is provided and the ouput of the main steam pressure controller provides a cascade setpoint to the steam flow controller.

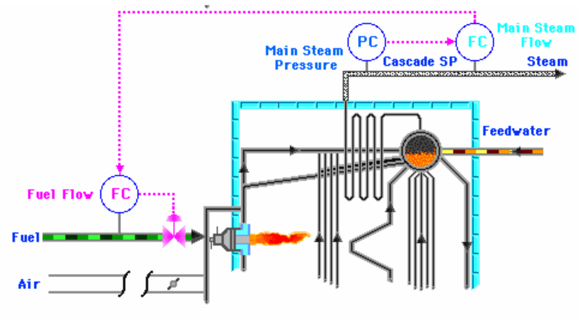

Fig. 4-14: Steam Pressure Control using cascaded Steam Flowrate

This compensated main steam pressure controller's output or the output of the steam flow controller is called the *Boiler master signal* and it determines the fuel and the air demand.

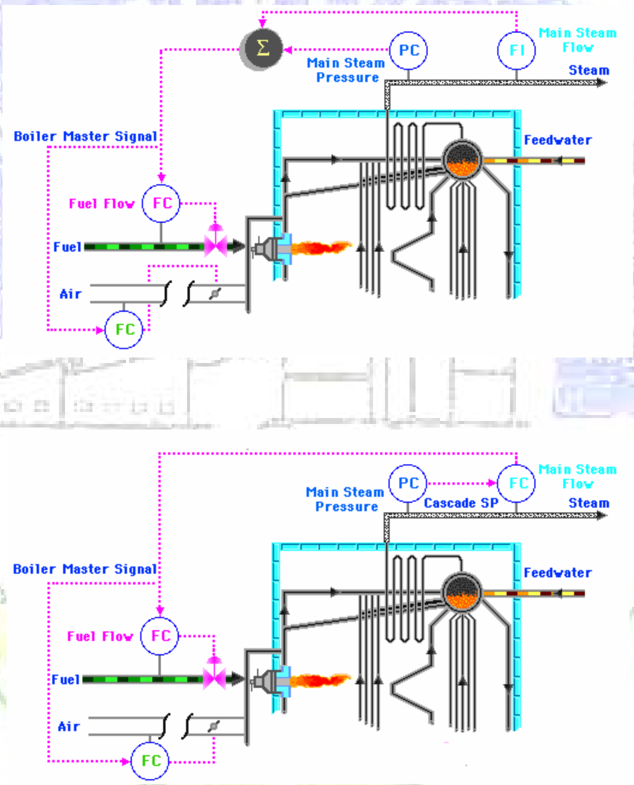

Fig. 4-15: Boiler Master Signal

As we know, the main steam pressure controller controls the boiler fuel and the air flow rates. Additionally, an HP header pressure controller is provided to control the HP header pressure by letting down the excess HP steam to the MP header. Normally, the HP steam pressure controller has a higher setpoint than the HP steam header pressure. The MP steam header pressure controller controls the MP header pressure by adjusting the let-down steam from the HP steam header or by adjusting the let-down steam to the LP steam header. The LP steam header pressure controller controls the LP header pressure by either letting down excess steam from the MP header or by venting the excess steam from the LP header.

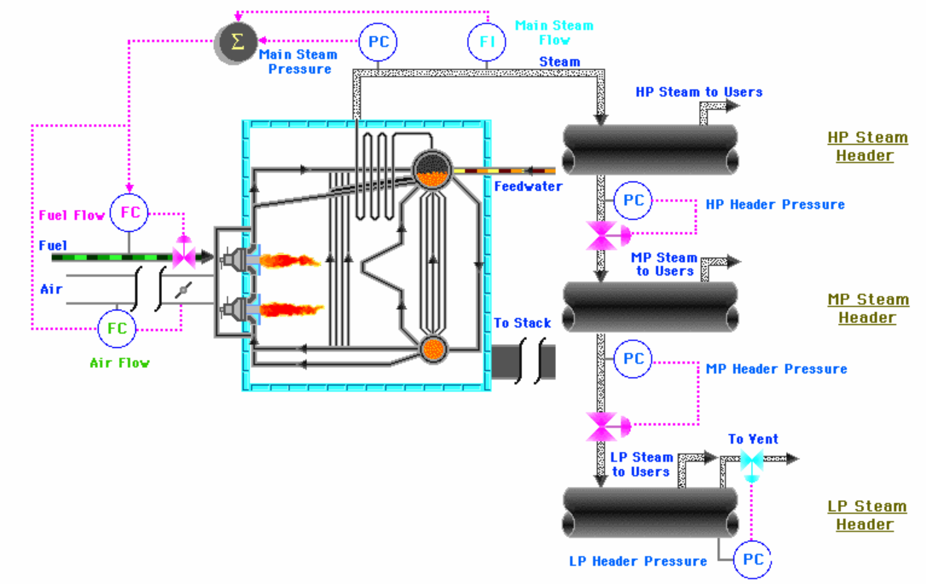

Fig. 4-16: HP and MP Header Pressure Control

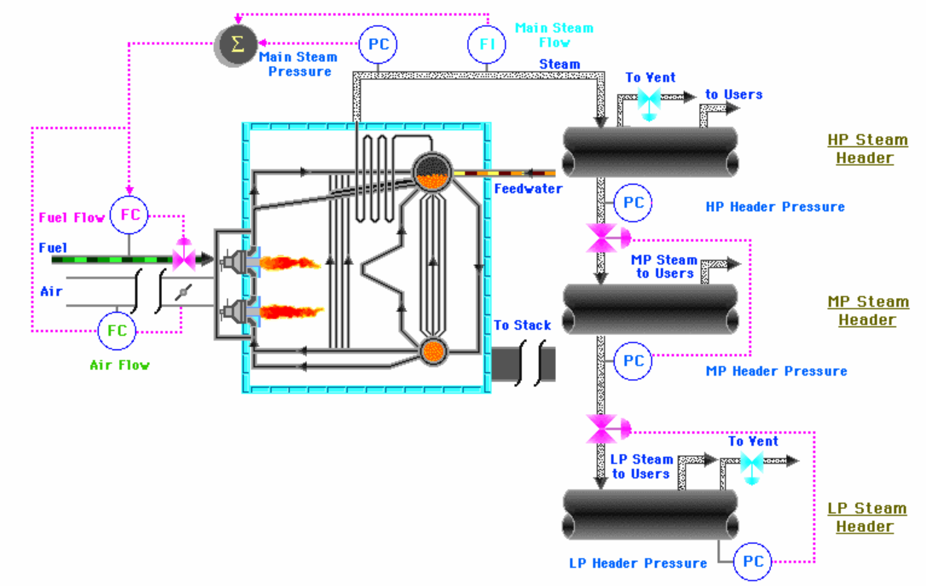

Fig. 4-17: MP and LP Header Pressure Control

4.4 Fuel Control

The boiler master signal ranges from 0 to 100% and it represents the total fuel flow demand. For those boilers that use only fuel gas or fuel oil for firing the boiler master signal represents the percent setpoint for the fuel flow rate controller. Some boilers use both fuel oil and fuel gas simultaneously. In this case the boiler master signal needs to be split into fuel oil and fuel gas demands. For this purpose normally a user setable fuel bias is provided that splits the boiler master signal into fuel oil and fuel gas demands. Sometimes the total calorie of the fuel oil or its instrument range may not be equal to the total calorie of the fuel gas or its intrument range. Hence, an additional correction is required to compensate for the calorific value difference between fuel oil and fuel gas.

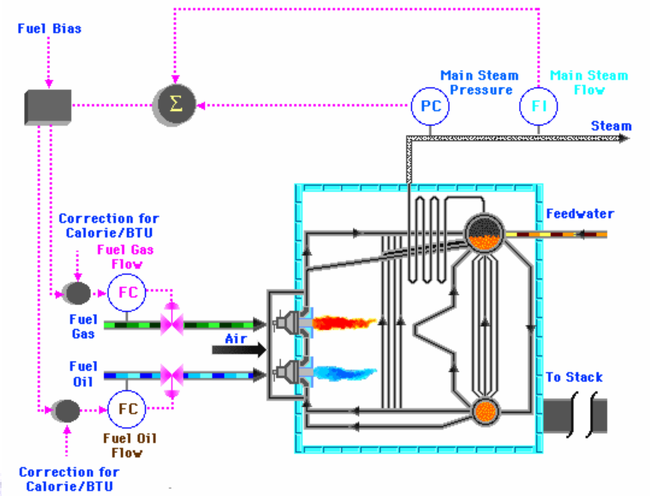

Fig. 4-18: Fuel Control for combined usage of oil and gas

4.5 Total Calorie Control

In simultaneous oil and gas firing any change in the composition of the fuel may lead to poor control of the boiler's key parameters. A *total calorie control* is used to take into account any changes in the fuel calorific value. Normally, the signal from the boiler master cascades in a total calorie controller. The PV value of the total calorie controller is calculated based on the current fuel oil and fuel gas flow rates and their respective calorific values. The output of the total calorie controller determines total fuel and air demand. The total fuel flow rate demand is split into fuel oil and fuel gas demand by considering the calorific value of each fuel. With the total calorie controller as the fuel composition changes the fuel flow rate is adjusted immediately to maintain the total heat released and hence the boiler pressure. Without a total calorie controller as the fuel composition changes the heat release in the boiler changes. This effects the steam generation and the steam pressure. The boiler master then adjusts the fuel to maintain the pressure, but the boiler conditions may be disturbed and may undergo a major transient. In summary a total calorie controller minimizes the disturbance to the boiler for changes in the fuel composition.

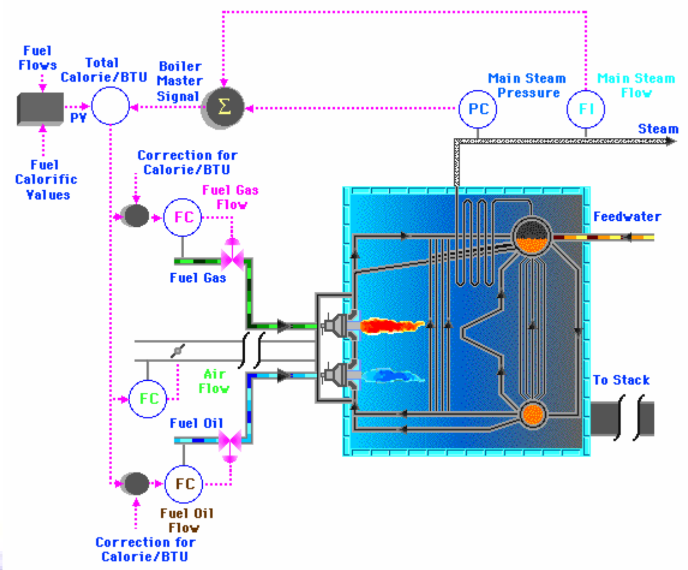

Fig. 4-19: Total Calorie Control

4.6 Combustion Air Control

In a forced-draft boiler the total air flow rate is controlled by adjusting the vanes of the FD fan. The air flow rate at individual burners can be adjusted by manipulating the air registers at each burner. The main air flow dock has a damper and its position is adjusted to maintain adequate draft and hence the total air flow rate. The air demand or the setpoint for the air flow rate controller comes from the boiler master signal. Sometimes the boiler master signal is scaled to assure that adequate amount of air is supplied for complete combustion of fuel. Sometimes an additional scaling may also be required to consider any changes in the fuel calorific value.

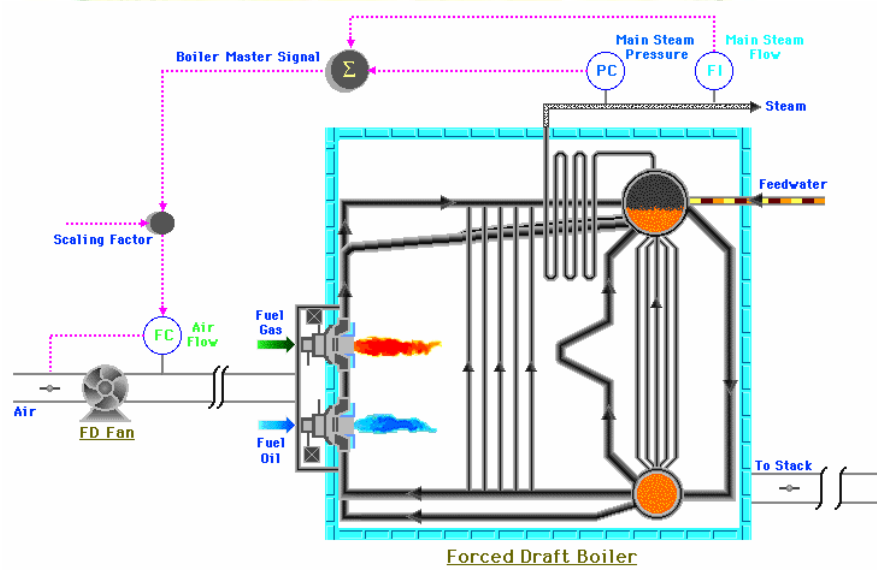

Fig. 4-20: Air Flow Control

4.7 Oxygen Control

For efficient boiler operation the excess air or oxygen in the flue gas needs to be controlled. Oxygen can be controlled by using an oxygen controller or by providing an user adjustable oxygen bias. The output of the oxygen controller or the oxygen bias is added to the measured air flow rate. The air flow rate controller takes this compensated air flow rate as its input, i.e. the PV value. Thus, the air flow rate controller adjusts the air flow rate for the desired oxygen.

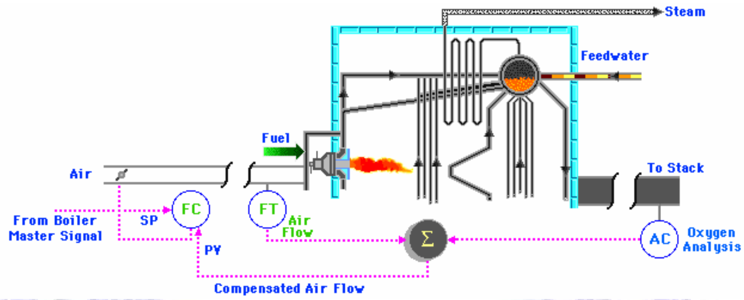

Fig. 4-21: Oxygen Control using an Oxygen Controller

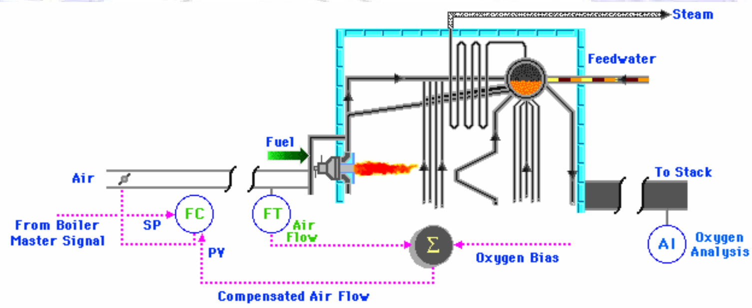

Fig. 4-22: Oxygen Control using a Bias

4.8 Cross Limit Control

As the boiler load changes the fuel flow rate and the air flow rate are continuously manipulated. The *cross limit control strategy* is used to ensure that there is always adequate air supply for any change in the fuel demand. Typically, there are two cross limits:

- Air side cross limit
- Fuel side cross limit

4.8.1 Air side Cross Limit

The air flow rate demand is calculated based on the boiler load, i.e. the boiler master signal. However, for better boiler efficiency it is better to calculate the air demand based on the current fuel flow rate. At the steady state condition the air demand computed by the two methods is equal. However, the air demand differs only during transients, e.g. during load changes. In the air side cross limit control the air demand is calculated based on the maximum of the boiler master signal and the air flow rate required to burn the current fuel entering the firebox.

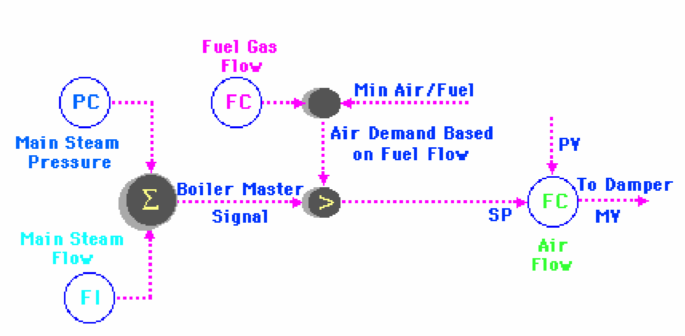

Fig. 4-23: Air side Cross Limit

Air cross limit control strategy ensures that during load reduction the minimum air flow required for complete combustion is always met and the air flow is reduced only after the fuel flow rate is reduced.

4.8.2 Fuel side Cross Limit

The fuel flow demand is also computed in two ways. One from the boiler master signal and another from the current flow of air. In the fuel side cross limit control the fuel demand is calculated based on the minimum of the boiler master signal and the fuel flow rate required based on the current air entering the firebox.

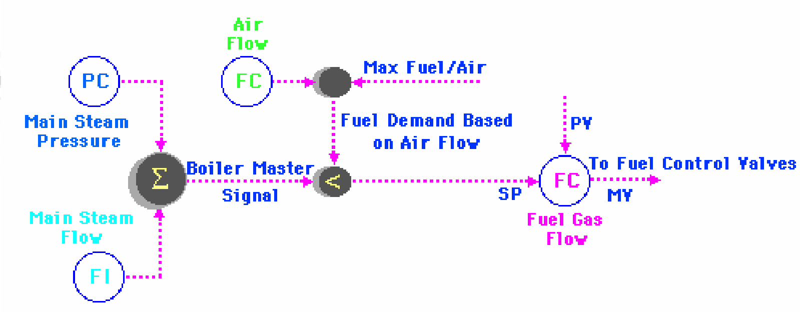

Fig. 4-24: Fuel side Cross Limit

Fuel cross limit control strategy ensures that during load increase the fuel flow is increased only after the air flow is increased.

5 Boiler Trips and Interlocks

The interlocks and trips are necessary to prevent dangerous situations which may arise during boiler operations. Typically, the boiler unit is provided with an interlock mechanism which when activated cuts the fuel flows to the burners and stops combustion. Please note that after the trip the air flow system continues to operate to cool the boiler and purge any unburnt fuel.

5.1 Trip Logic

Trip Logic is implemented in all modern boilers with the objective of providing safety. Emergency trip valves are placed in the main fuel lines and in the pilot gas line. Whenever a trip condition is detected these trip valves are closed automatically.

Some typical causes for a boiler trip are:

- Low Steam Drum Level,
- Low Air Flow and
- Low Fuel Pressure.
-

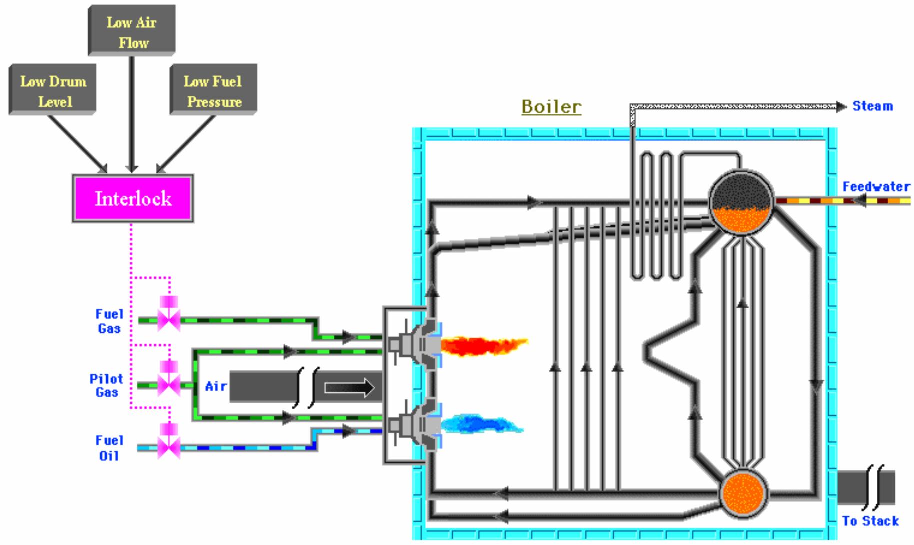

Fig. 5-1: Boiler Interlocks

For example, if the steam drum level becomes low, there is a chance that the drum may become empty. If this situation is allowed to continue with all burners firing, it may lead to severe tube damage with possible meltdown.

In the case of low air flow it leads to incomplete combustion and the unburnt fuel accumulates in the firebox.

Similarly, at low fuel pressure the amount of fuel sent to the burners becomes low. The flame extinguishes and the unburnt fuel accumulates in the firebox. An accumulation of the unburnt fuel in the boiler is a very dangerous situation and if the fuel flow is not stopped immediately, it may lead to fire and explosion.

Most modern boiler units are provided with a single emergency trip switch which when activated automatically closes the fuel and the pilot gas trip valves. The trip valves can also be closed manually by triggering their respective individual switches.

Please note that the emergency trip switch can also be used to perform manual shutdown. In order to open the trip valves manually certain permissive, like purge complete, must be met.

5.2 Purge Logic

After a shutdown or interlock trip there is a possibility of accumulation of unburnt fuel in the firebox. This unburnt fuel can possibly catch fire and damage the boiler. Hence, before igniting the burners it must be purged with air to remove any accumulated unburnt fuel. Typically, certain conditions have to be met before purging can commence. For example,

- Steam Drum Level is normal and
- Combustion Air Flow is normal.

These conditions should hold true during the entire purging operation which is usually through a period of 5-30 minutes. Usually, a switch is provided to commence purging.

After the purging operation is complete the manual open permissives are granted for the fuel oil and fuel gas trip valves. In other words, they can be opened manually.

Please note that if at any time during purging the steam drum level or the combustion air flow becomes abnormal the boiler needs to be re-purged after the situation corrected.

6 Basic Operations

In this chapter we are going to learn about the operating principles of a typical forced-draft drum type boiler. This includes

- Pre-Startup,
- Start-up,
- Shutdown and
- Post-Shutdown

operations.

6.1 Pre-Startup Operations

Before starting a boiler the entire boiler unit has to be checked and all equipment inspected. This ensures safety during boiler start-up operation. The following inspection should be mandatory before start-up of the boiler unit.

6.1.1 Inspection of Equipment

- Inspect the entire boiler unit for any abnormal condition, such as warping of the heating tubes.
- Ensure that no scales or deposits are on the heating tubes and there is no spillage of fuel or water in the firebox.
- Ensure that the boiler unit has been tested for leakage. Ensure that utilities such as instrument air or electricity are available.
- If steam is required for equipment like the FD fan and feed water pump turbines, air pre-heaters and feed water pre-heaters, check the availability of steam from other boiler systems.
- Inspect all rotational equipment, feed water pumps, air pre-heaters and forced-draft fans to ensure that they are ready for operation. Also inspect the back-up devices.

6.1.2 Inspection of Lines

- Ensure that all controllers are in manual mode and that the associated valves are in proper positions.
- Ensure that all drain and vent valves are closed.
- Inspect all transmitters, sensors and draft gauges to ensure that they are in satisfactory condition.

- Check all air registers and air dampers for their correct movement. Also check their positions.

6.1.3 Inspection of Fuel System

When oil is used as fuel:

- Ensure that the fuel oil pump is ready for operation.

- Purge the fuel oil line with an inert gas like nitrogen to eliminate oxygen or any other combustible gas.

- Start the fuel oil pump and commence the circulation of fuel oil at the normal temperature and pressure conditions.

This ensures immediate availability of fuel oil during the start-up of burners. If fuel oil heaters are present commission them.

When gas is used as fuel:

- Warm up the gas fuel lines with steam tracing. If the fuel gas lines are not sufficiently heated, traces of water vapor present in the fuel gas may condense in the fuel gas lines. This will block the flow of flue gas.

The pre-startup operation is now complete and the boiler unit is ready for start-up.

6.2 Start-up Operations

A boiler unit can be started up in more than one way.

In plants where more than one boiler is connected to a common header the load of each boiler is controlled by a boiler load controller.

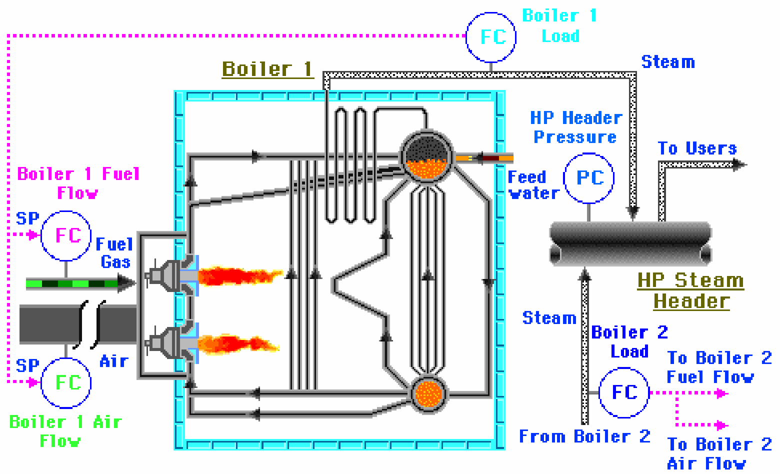

Fig. 6-1: Boiler Load Control for multiple Boilers connected to a header

Above 10% load the boiler load controller is placed in automatic mode and the air and fuel low rates are manipulated by this controller. The boiler load is gradually increased and it is brought to its design operating condition. The boiler unit is then placed in full automatic control.

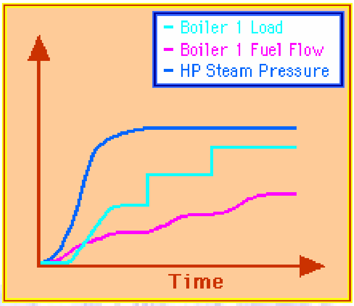

Fig. 6-2: Increasing the Boiler Load during Start-up (multiple Boilers)

In case a single boiler is connected to the steam header used for supplying steam a different start-up strategy is used.

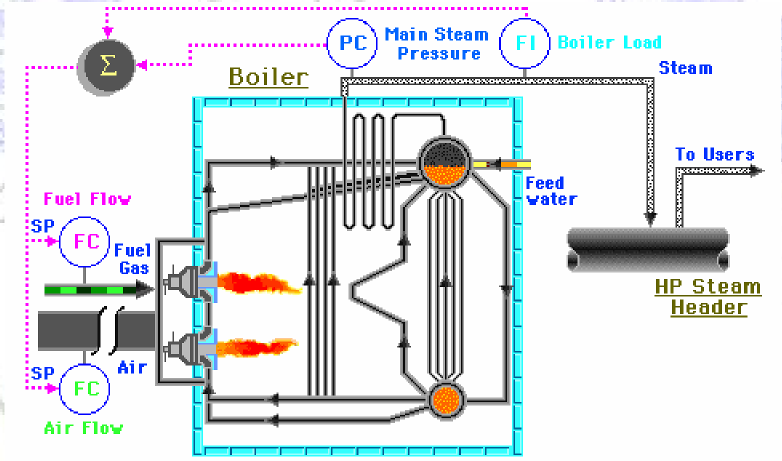

Fig. 6-3. Steam Pressure Control for a single Boiler

The boiler is brought up to some low load, say 10%, in manual control. By this time the boiler should attain the design pressure and it is placed in fully automatic control. The steam demand flow is then gradually increased and the boiler is brought to its design operating condition.

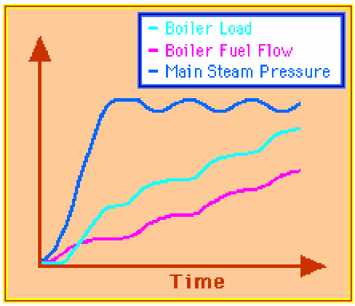

Fig. 6-4: Increasing the Boiler load during Start-up (single Boiler)

Please note that in any case before starting up the boiler unit ensure that all controllers are in manual mode and all the valves are completely shut.

6.2.1 Feed Water Circuit

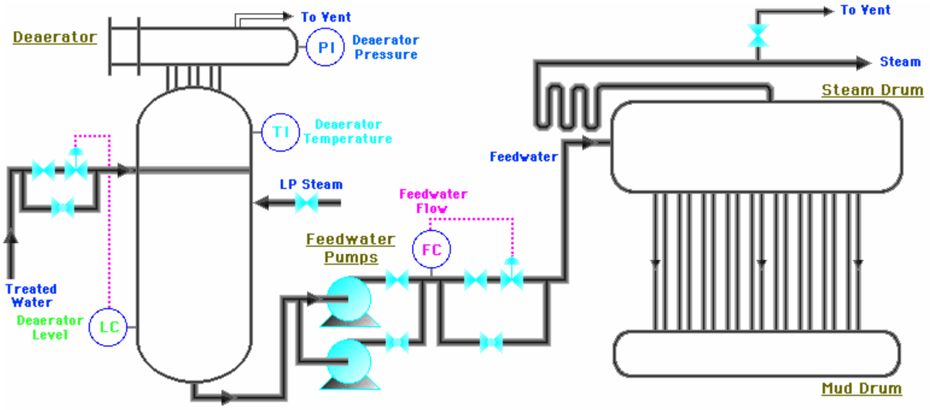

Fig. 6-5: Feedwater Circuit before Start-up

- The first step in the start-up of the boiler is to deaerate the treated water. Gradually introduce the treated water into the deaerator by using the control valve or the bypass valve. The level of water in the deaerator slowly builds up. When the deaerator is filled to half of its capacity, start controlling its level by using the level controller. This is done by placing the level controller in automatic mode and providing the appropriate setpoint. Now introduce the LP steam into the deaerator. Wait until the pressure and the temperature in the deaerator stabilizes.

- Now the deaerated water can be introduced into the steam drum. Start the boiler feed water pumps and gradually introduce the feed water into the steam drum by using the control valve or the bypass valve. The level of the steam drum gradually increases and when it is filled to half of its capacity, stop the feedwater supply by closing the appropriate valves. Now, open all the vent valves in the main steam line to release any air locked in the steam line.

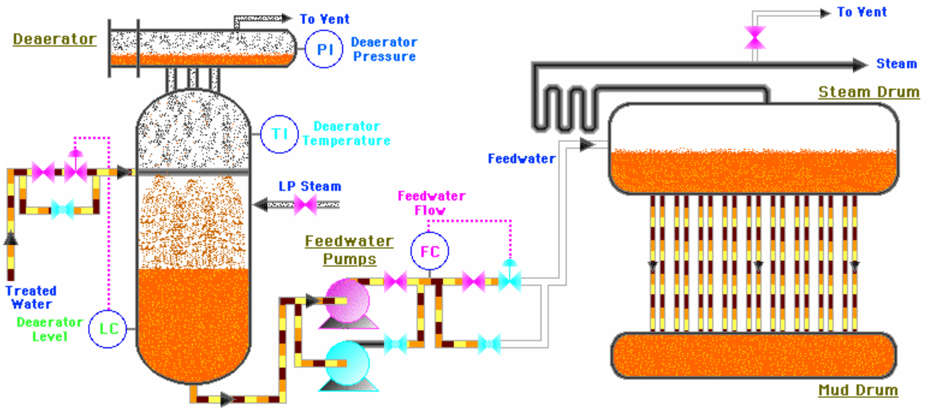

Fig. 6-6: Prepared Feedwater Circuit

6.2.2 Air Circuit

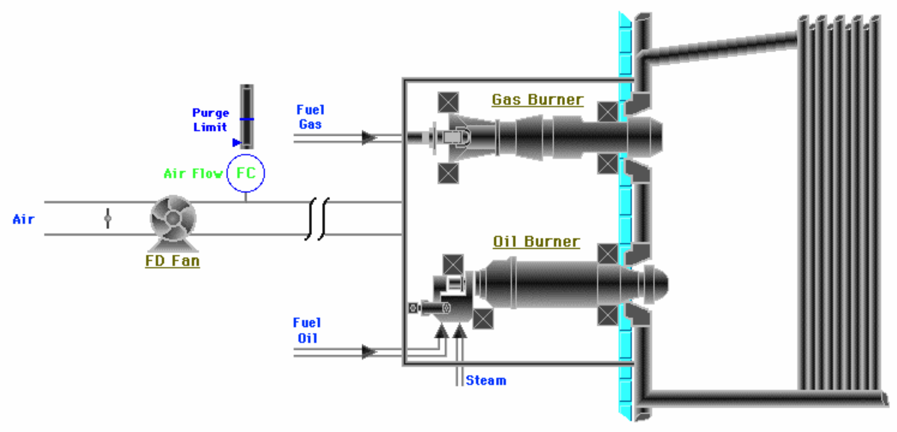

Fig. 6-7: Air Circuit before Start-up

- Fully open the air registers of all the burners.
- Place the air damper at its minimum position. Normally, it will supply adequate air and draft to satisfy the air purge limit.
- Slightly open the vane of the forced-draft fan and start the forced-draft fan.
- Adjust the FD fan vane position to maintain the air flow rate above the purge limit.

6.2.3 Purging

The main burners should not be ignited until all the combustible gases in the firebox are expelled. Most boilers have a purge logic that does not allow the operator to open the fuel trip valves until the boiler has been purged with air for a certain period of time. The purging operation is normally commenced by triggering a purge start switch. During the purge operation a timer monitors purge conditions like

- Air Flow Rate
- Steam Drum Level
- etc.

When the purge timer expires and all conditions are met the purge operation is complete. Now, open permissive is granted for the fuel trip valves and the operator can manually open them.

6.2.4 Ignition of Pilot Burner

The next step in the start-up of the boiler is the ignition of pilot burners.

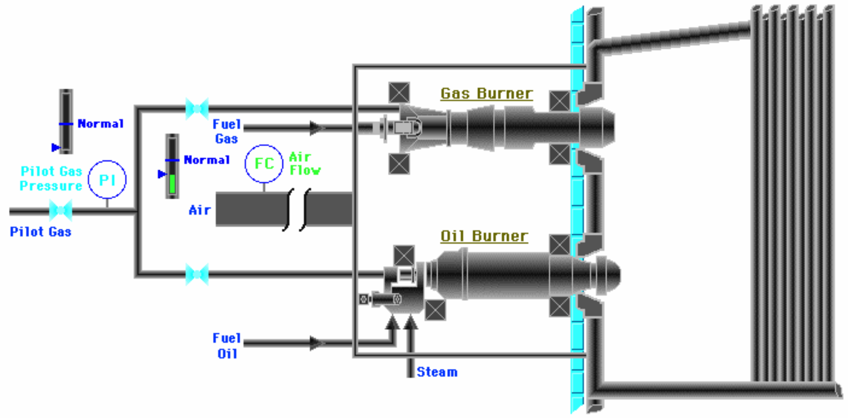

Fig. 6-8: Burners before Start-up

- Gradually open the fuel valve in the pilot gas line until the desired gas pressure for pilot ignition is build.
- Energize the ignition transformer to ignite the pilot gas burner. In some boilers the purge logic locks the electricity to the ignitor until purging is complete.
- Open the pilot gas valve at the upstream of the burner to maintain the pressure.
- If necessary, alter the air flow rate to maintain the pilot flame.
- During the ignition a low flow rate of pilot gas should be maintained. The pilot gas valve at the burner inlet should never be opened too rapidly. However, sufficient pilot gas should be allowed to maintain adequate pressure.

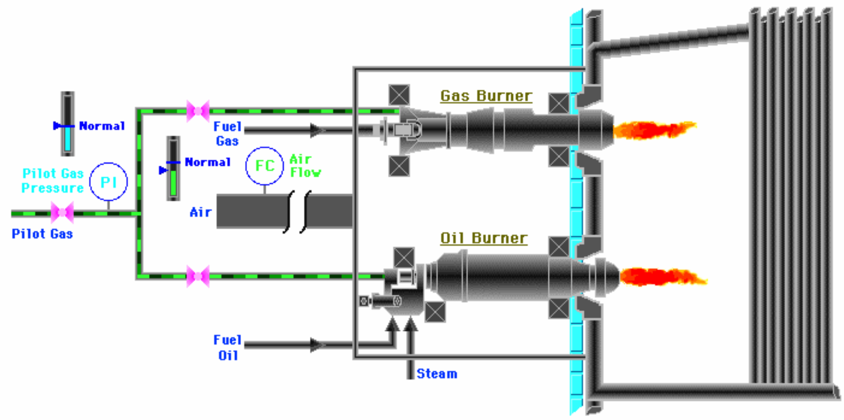

Fig. 6-9: Burners after Ignition of Pilot Burners

6.2.5 Ignition of Main Burner

It is important to commence firing of main burners with low fuel flow. Also, care must be taken to inject the correct quantity of air. Please note that a large fuel flow can sometimes prevent ignition. Very high air may delay ignition or may blow out the flame.

Gas Burner

- Before starting the gas burner if air pre-heaters are present in the air circuit commssion them.

- For igniting the gas burners open the trip valve in the fuel gas line. Gradually open the fuel gas flow control valve to raise the fuel gas pressure at the burner inlet.

- The main burner gets ignited automatically with the help of its pilot flame.

- Ignite only one or two burners during the initial phase of start-up.

- Stabilize the flames by adjusting their air registers.

- Continuously monitor the oxygen, hydrocarbon and the carbon monoxide levels in the flue gas.

- Periodically adjust the FD fan damper to maintain the oxygen content in the flue gas within the desired range. The excess oxygen in the flue gas should be maintained to ensure complete combustion by avoiding traces of hydrocarbon or carbon monoxide in the flue gas.

- During ignition ensure that the fuel gas pressure at the burner inlet is above its minimum value. If the pressure falls below its minimum value, the flame becomes unstable and may go out.

- If any problem arises when igniting the main burners, immediately close the burner gas valves. This avoids accumulation of unburnt fuel in the firebox.

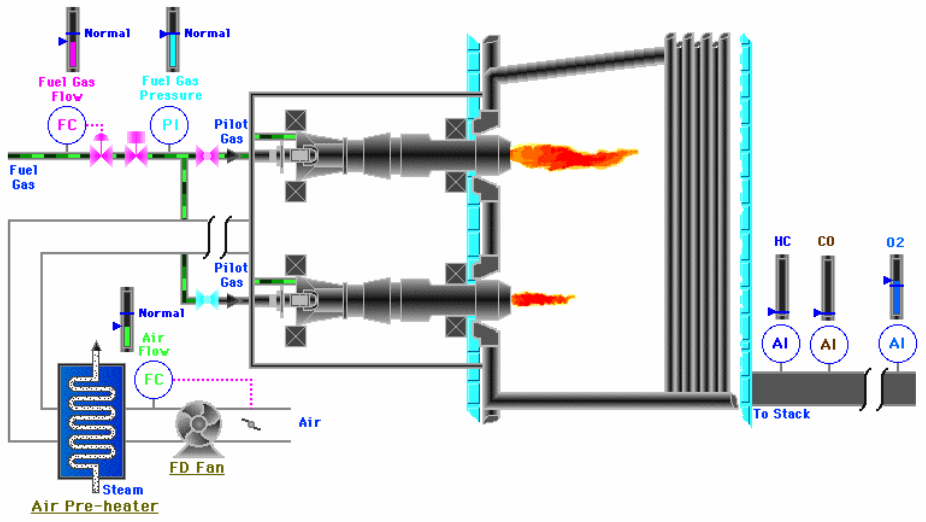

Fig. 6-10: Burners after Ignition of a main Gas Burner

Oil Burner

- For igniting the oil burner open the trip valve in the main fuel oil line.
- Gradually open the fuel oil control valve to raise the fuel oil pressure at the burner inlet.
- Before injecting the atomizing steam completely drain the steam line to avoid water accumulation in the firebox.
- Now, gradually inject the atomizing steam.
- Slowly open the fuel oil valve at each burner inlet to allow minimum fuel oil flow.
- The main burner gets ignited automatically with the help of its pilot flame.
- Ignite only one or two burners during the initial phase of start-up.
- Oil-to-steam ratio must be maintained at the desired value to ensure proper ignition and stable combustion at the main burner. An inproper ratio makes ignition difficult and can cause the flame to go out. Most modern boilers have an automatic controller to maintain the oil-to-steam ratio.
- Stabilize the flame by adjusting the air registers.
- Continuously monitor the oxygen, hydrocarbon and the carbon monoxide levels in the flue gas.
- Periodically adjust the FD fan damper to maintain the oxygen content in the flue gas within the desired range. The excess oxygen in the flue gas

should be maintained to ensure complete combustion by avoiding traces of hydrocarbon or carbon monoxide in the flue gas.

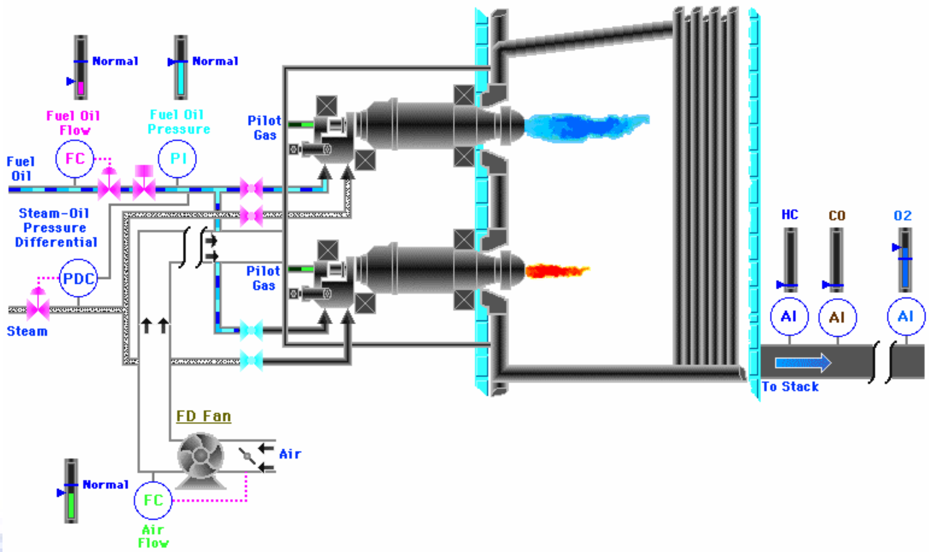

Fig. 6-11: Burner after Ignition of a main Oil Burner

6.2.6 Re-supply of Feed Water

- As the water temperature rises the steam drum level initially increases due to the expansion of water. When steam generation commences in the steam drum, its level starts decreasing.
- Regularly supply feed water to the steam drum to maintain the steam drum level, but do not overfill it.
- If a feed water pre-heater exists, introduce the steam to heat the feed water.

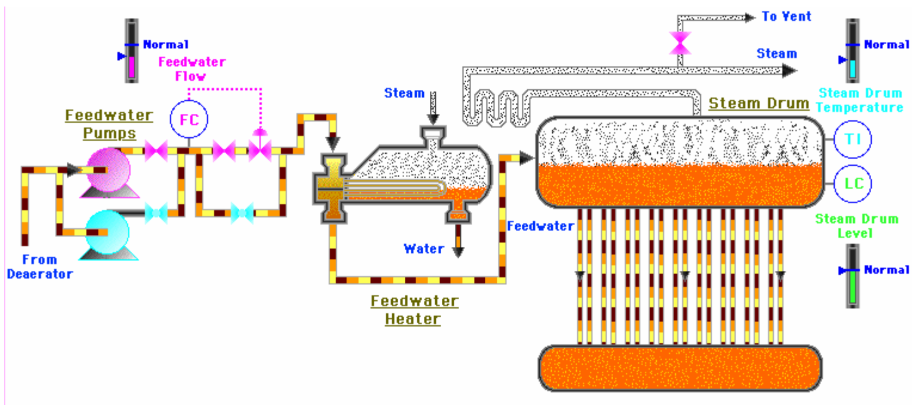

Fig. 6-12: Feedwater System and first Steam Generation

6.2.7 Adjustment of Firing Rate

Once the burner flames are stabilized, place the fuel flow and air flow controllers in automatic mode. Continue to increase fuel supply to the burners to increase the steam temperature and the steam pressure at the recommended warm-up rate. The warm-up rate varies from one start-up to another depending on the steam drum conditions.

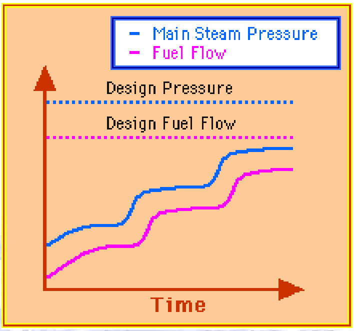

Fig. 6-13: Courses of Pressure and Fuel Flow acc. to recommended warm-up rate

Continue to adjust the combustion air flow to maintain the oxygen content in the flue gas within the desired range. With increasing the firing rate some burners may reach their maximum limit of combustion rate based upon their characteristic curves and may not sustain a stable flame. In that case identify additional burners to be lit for uniform heat distribution and ignite them.

6.2.8 De-Superheater

- Continuously monitor the steam temperature at the outlet of the superheater.
- When the steam temperature starts to rise above the desired value, introduce feed water to the de-superheater and then place the main steam temperature controller in automatic mode.

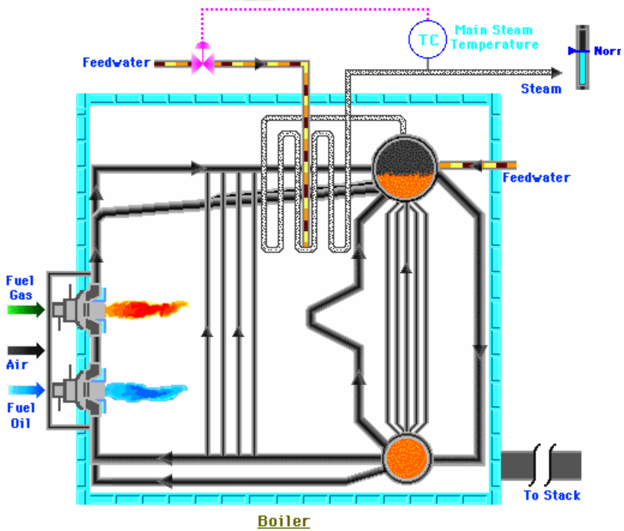

Fig. 6-14: Automatic Control of Steam Temperature with De-Superheater

6.2.9 Pressurization of Main Steam Headers

With increase in the fuel oil and fuel gas the steam pressure slowly builds up.

- As the pressure exceeds the high pressure limit, the HP header pressure controller will let down the excess steam to the MP steam header.

- As the MP header steam pressure exceeds its high pressure limit, the MP header pressure controller will let down the excess MP steam to the LP steam header.

- If the pressure of the LP steam header exceeds its high pressure limit, the LP header pressure controller vents the excess steam.

Now the HP, MP and LP steam are ready to be extracted for downstream processes.

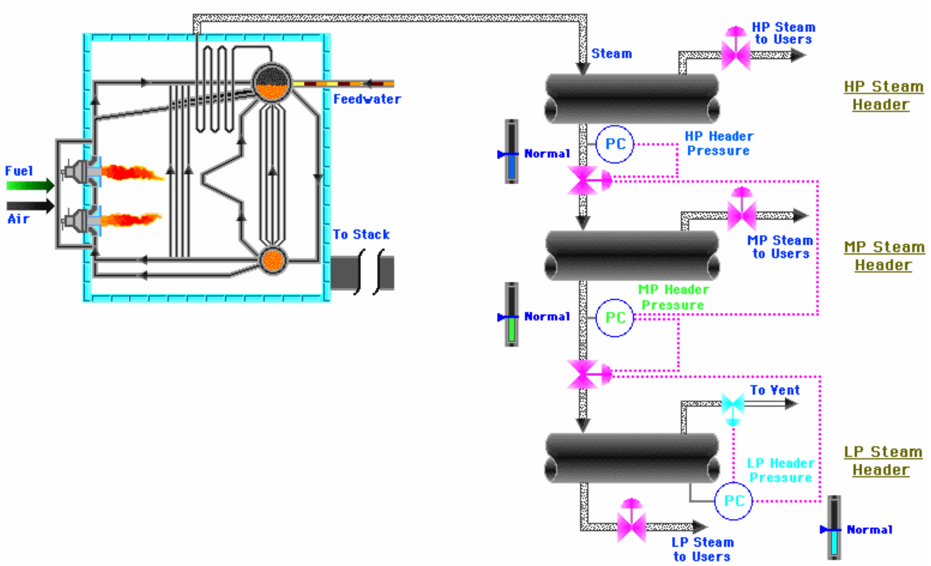

Fig. 6-15: Pressurization of Steam Headers

6.2.10 Getting to design conditions

- As the steam pressure stabilizes at some desired value, place the main steam pressure controller in automatic mode.

- Gradually turn the fuel flow and the air flow rate controllers to cascade mode without generating a bump.

- If an oxygen controller is present, it can be turned to automatic mode.

- Some boilers have a bias on their air flow measurement instead of the oxygen control. Adjust the bias to alter the oxygen level in the flue gas.

- Gradually increase the steam withdrawal rate and bring the boiler unit to design operating condition.

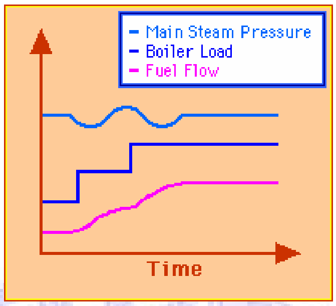

Fig. 6-16: Gradual Increase of Boiler Load

- Open the blowdown valves on the steam drum to commence continuous blowdown.

- Periodically perform the blowdown operation from mud drum.

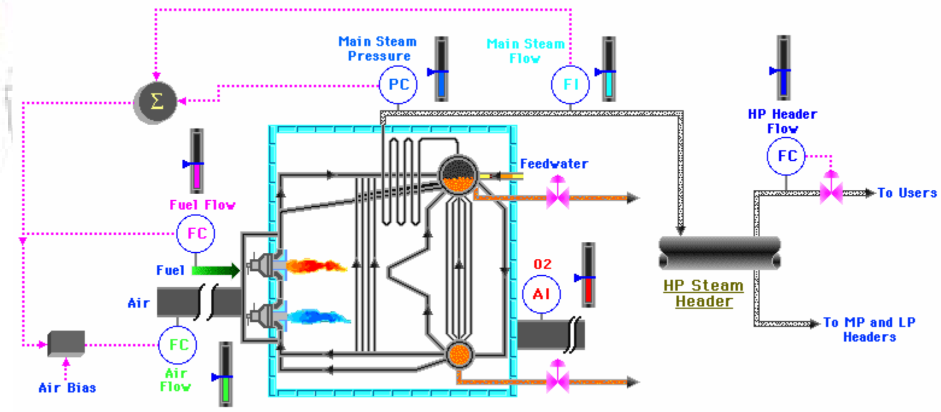

Fig. 6-17: Operating at design conditions

The start-up operation of the boiler is now complete.

6.3 Shutdown Operations

Like start-up the shutdown of a boiler can be done in many ways.

When more than one boiler is connected to a common header the typical strategy is to take the boiler master load controller in automatic mode and slowly decrease the firing rate. This gradually decreases the boiler load. This operation is continued until the boiler load drops to very low load, say 5%.

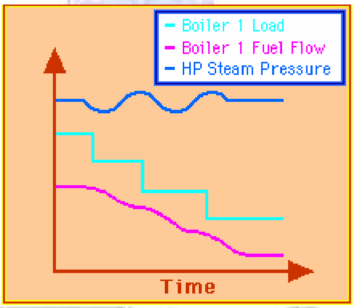

Fig. 6-18: Gradual Decrease of Boiler Load

The boiler is then shutdown manually by triggering the emergency shutdown button. While this boiler is shutting down the main steam pressure controller adjusts the boiler load of the other boilers to control the steam pressure.

In the case of a single boiler with a header the boiler is shutdown with the main steam pressure controller on.

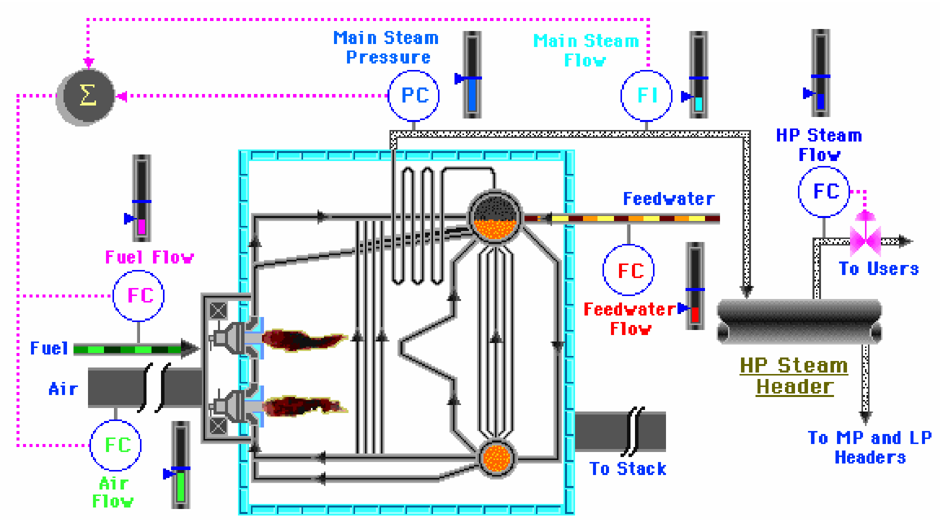

Fig. 6-19: Control Structure of a single Boiler connected to a header

- In a single boiler with a header place the air flow controller in automatic mode and fully open the air registers of all the burners. During shutdown for safety purposes the excess air rates of all the burners are kept higher than their normal values.

- As the load reduces the steam pressure goes up. To bring the steam pressure back to the design value the main steam pressure controller reduces the fuel flow to the burners. The feed water flow into the steam drum is also simultaneously reduced.

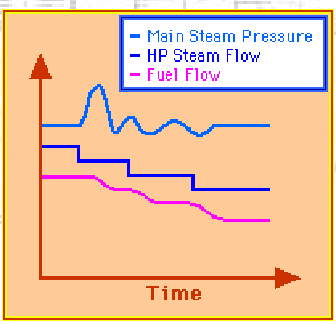

Fig. 6-20: Gradual Decrease of Boiler Load

- When the boiler load is reduced to around 20% place the feed water flow, fuel flow and air flow controllers in manual mode.

- Continue to reduce the steam withdrawal rate of all the headers. The fuel and the feed water flows need to be reduced proportionally.

- Adjust the air flow rate to avoid flame out occuring in the burners due to excess air. As the fuel flow rate decreases the fuel pressure at the burner inlet also decreases.

- If the fuel pressure at the burner inlet becomes less than the stable combustion range, extinguish one of the burners. Please note that the burners should not be extinguished simultaneously. Always extinguish only one burner at a time. In a combination oil and gas burner initially use either the oil or the gas burner to reduce the fuel. Normally, the oil burner is shut off first, because it has a narrow operating range. The gas burner is shut off later, because it has a wider operating range than the oil burner. After an oil burner is shut off load steam to the extinguished burner to expell the remaining oil in the burner. Ensure that all pilot burners are on, so that the purged oil vapors are burnt. After the gas burner is shut off, purge the burner with an inert gas like nitrogen. Continue to keep the pilot burner on, so that the purged fuel gas is completely burnt.

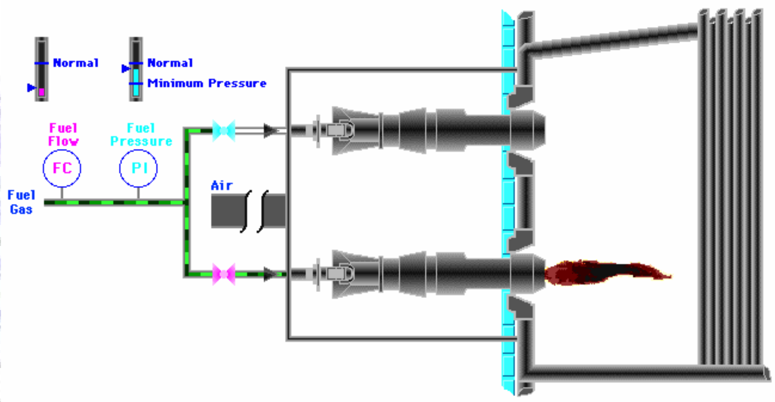

Fig. 6-21: Extinguishing of main Burners

- Continue to extinguish the burners one after another till all the main burners are shut off.

- Now, completely close the fuel trip valves.

- For safety purposes do not shut the pilot burners until the fuel trip valves are closed.

- Manually trip the boiler unit by triggering the emergency trip switch.

6.4 Post-Shutdown Operations

After shutdown of a boiler certain operations need to be performed based on when the boiler unit needs to be restarted.

- In any case, open all air registers of the burners and purge the firebox with air.

- If an immediate start-up is planned, do not drain the steam drum, but maintain the level around the design value.

- If an immediate start-up is not planned, fully close all the block valves and control valves to prevent any leakage into the boiler.
- After the steam generation stops, close all blowdown valves.
- Stop the feed water supply.
- Completely drain the steam drum and all the other vessels.
- Stop all pumps and fans.

The shutdown of the boiler is now complete.

7 Normal Operations

The steam load of a boiler varies with the changes in the steam requirements in the downstream processes. Due to such continuous load changes the entire boiler unit is constantly disturbed. This effects the key boiler parameters like the steam pressure, temperature and the steam drum level. Normally, the advanced control system responds to these changes by bringing the key process variables back to the desired value. The settling time depends on the extent of the upset and the controller tuning. Hence, it is important to understand how load changes effect the boiler unit.

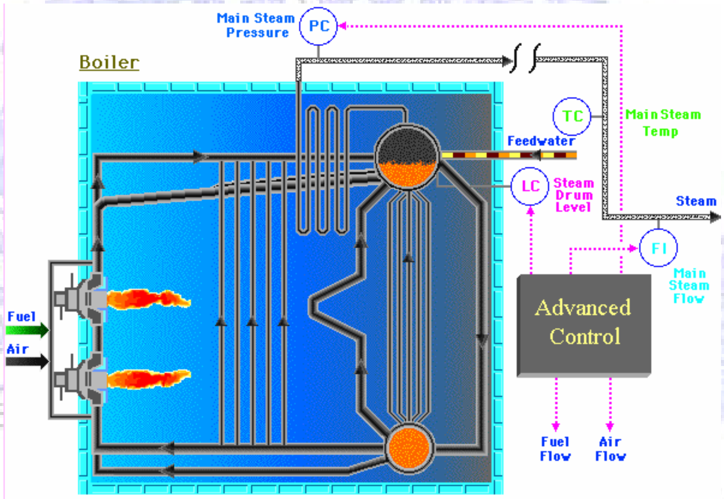

Fig. 7-1: Boiler Unit using Advanced Control

7.1 Effect of Load Changes on Pressure

Let us consider the effect of increase in the HP steam header load on the boiler unit.

As more steam is drawn from the HP header its pressure comes down. As we know the main steam pressure controller is the master controller that provides the setpoints to the fuel flow and the air flow controllers. Due to decrease in the pressure the main steam pressure controller increases setpoints to the fuel flow and the air flow controllers. The fuel and the air flow rates increase and more fuel is burnt. Due to the higher firing rate more steam is produced and the HP steam header pressure increases. Gradually, the boiler unit settles at a new steady state condition.

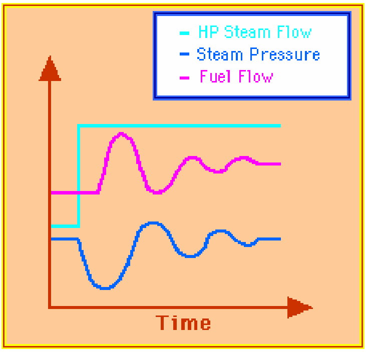

Fig. 7-2: Effect of increase in steam consumption on steam pressure

Conversely, when the HP steam consumption decreases, the HP steam pressure increases. The main steam pressure controller manipulates the setpoints of the fuel flow and the air flow rate controllers to decrease the firing rate and bring down the pressure.

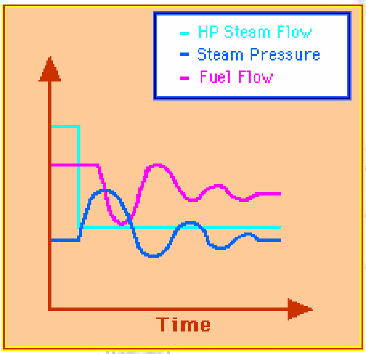

Fig. 7-3: Effect of decrease in steam consumption on steam pressure

Now, let us consider a load change in the LP steam header. Let us assume that the boiler has three headers, namely the HP, the MP and the LP steam header.

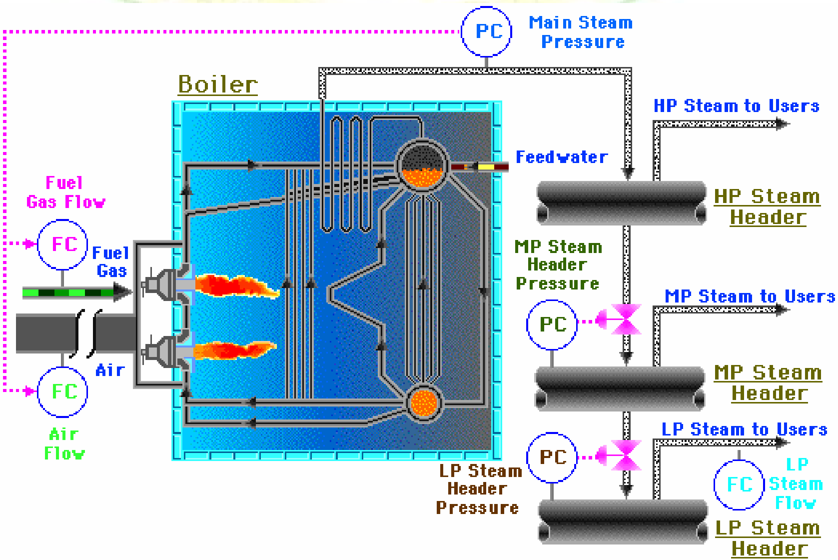

Fig. 7-4: Boiler Unit with HP, MP and LP Steam Headers

When the steam load of the LP steam header changes, its pressure changes. The LP steam pressure controller manipulates the MP letdown steam flow to bring the pressure back the design value. This effects the MP steam header pressure and the MP steam header pressure controller in turn manipulates the HP letdown steam flow rate to bring the pressure back to the design value. Thus, a change in the LP steam load cascades to the HP steam header and the main steam pressure controller manipulates the fuel flow to maintain the pressure.

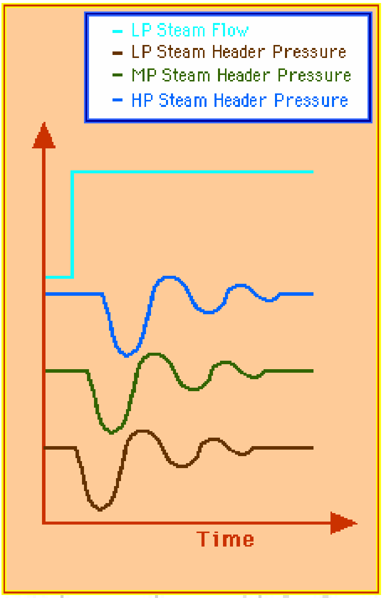

Fig. 7-5: Responses of Steam Header Pressures on increase in LP steam flow

The recovery of the boiler unit to changes in the load depends mainly on the advanced control system. Some possible causes for the sluggish response of the contol system are

- Lag in the measurement of the controlled variable,
- Slow response of the control valve or
- Tuning of the controllers.

If the response of the control system is slow, the upset to the steam pressure may be excessive. When the upset is expected to become excessive, a manual intervention is required to minimize the upset.

7.2 Effect of Load Changes on Steam Drum Level

When the steam load of a header increases suddenly, the steam drum level increases initially due to the swelling of steam bubbles trapped in the water.

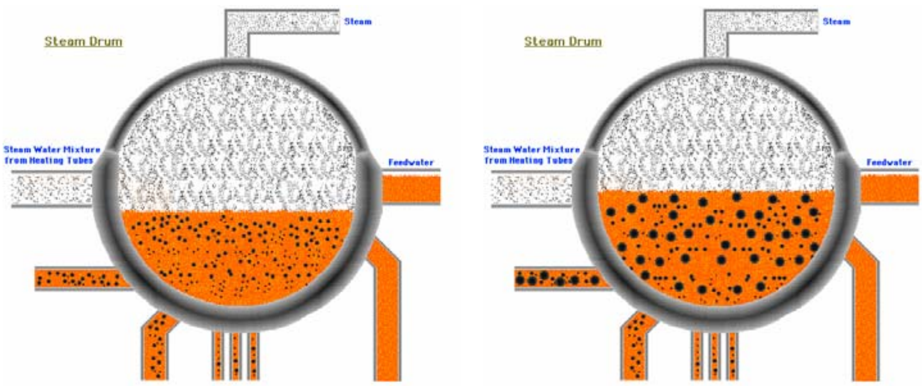

Fig. 7-6: Swelling of Steam Drum Level
due to sudden increase in steam consumption

Conversely, when the steam consumption of a header decreases suddenly, the steam drum level decreases initially due to the shrinking of the steam bubbles trapped in the water.

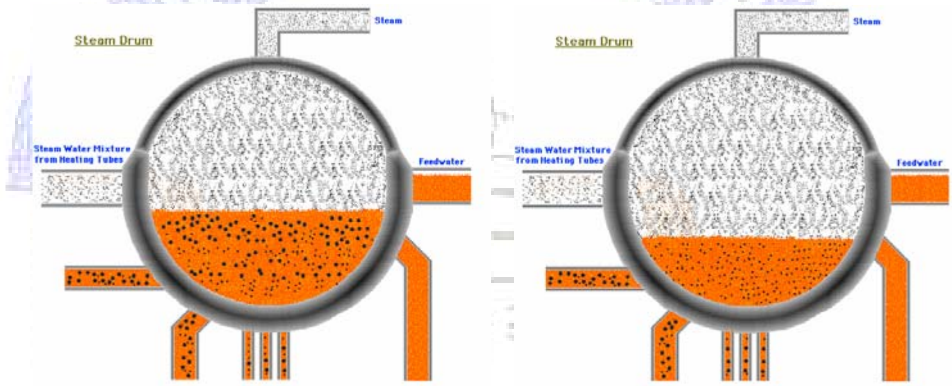

Fig. 7-7: *Shrinking of Steam Drum Level*
due to sudden decrease in steam consumption

Now, let us consider the use of the three-element control strategy to control the steam drum level.

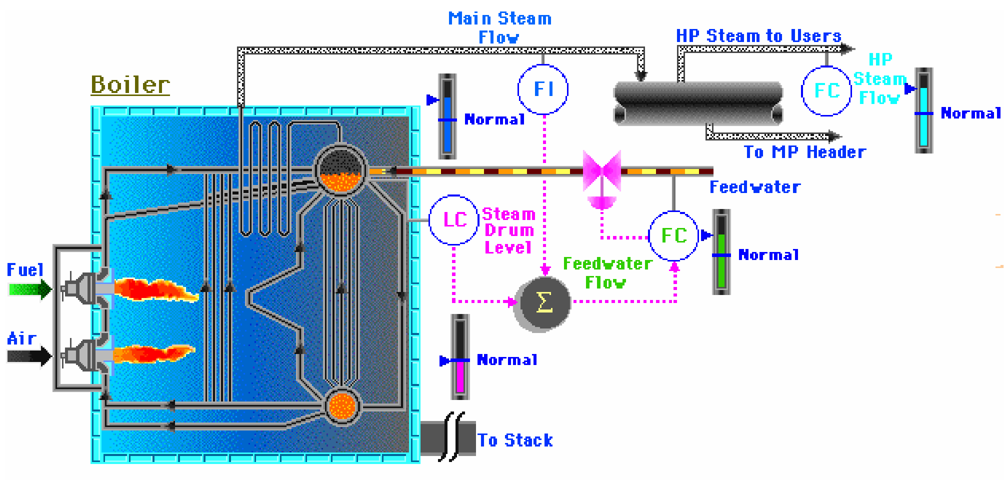

Fig. 7-8: Three-element feedwater control

When the steam load of a header is increased, more feed water is needed to maintain the steam drum level as more steam leaves the boiler. The three-element control immediately supplies more feed water to the steam drum and maintain its level. However, the recovery of the steam drum level to changes in the load depends mainly on the performance of the three-element control. If the response of the control system is sluggish, the level may become dangerously low.

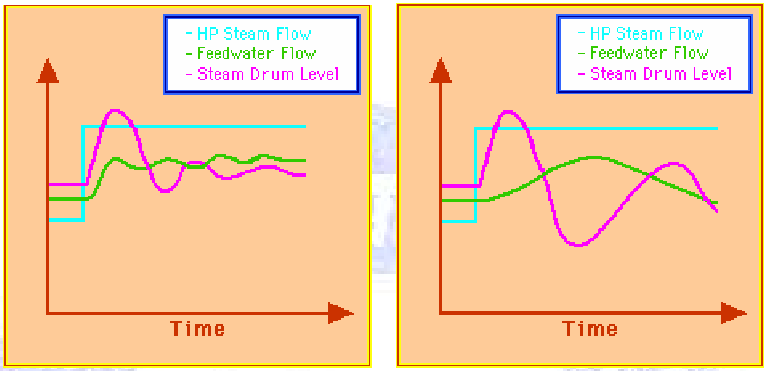

Fig. 7-9: Good vs. sluggish performance of three-element level control

Due to the geometry of most of the steam drums the rate of change of steam drum level is faster at low drum levels. Hence, it is extremely important to restore the level before the interlock logic trips the boiler due to the low level. At extreme conditions manual intervention of the control system may be required to speed up the level recovery.

8 Emergency Operations

In this chapter we are going to learn about the boiler emergency operating principles. Any emergency condition that may occur in the boiler can have adverse effects on the entire plant. Hence, it is extremely important to respond to an emergency situation in a timely and a safe manner. Most modern boilers have trip and interlock systems for safety purposes. Under extreme conditions the trip system shuts down the boiler automatically. When a trip signal is generated either automatically or manually, the emergency trip valves on the main fuel and pilot gas line are closed.

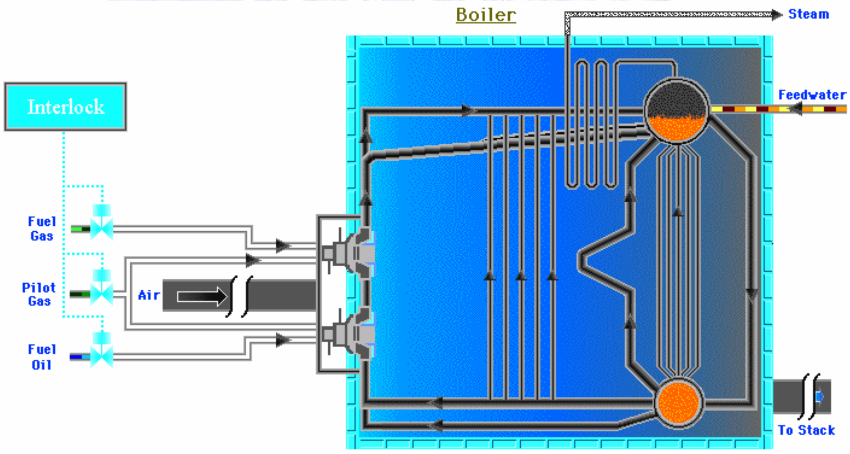

Fig. 8-1: Trip and Interlock System of a Boiler Unit

This prevents hazardous situations such as unburnt fuel in the firebox, high temperatures in the boiler, low water level in the steam drum etc.. Hence, it is important to detect abnormal situations early and take necessary corrective action before the boiler trips and effects the entire plant.

8.1 Low Steam Drum Level

When the boiler inventory in the boiler reduces, the steam drum level drops and the heating tubes get overheated. The overheating of tubes causes thermal stresses on tube metal and damages the tubes. Hence, most boilers have a low level automatic trip.

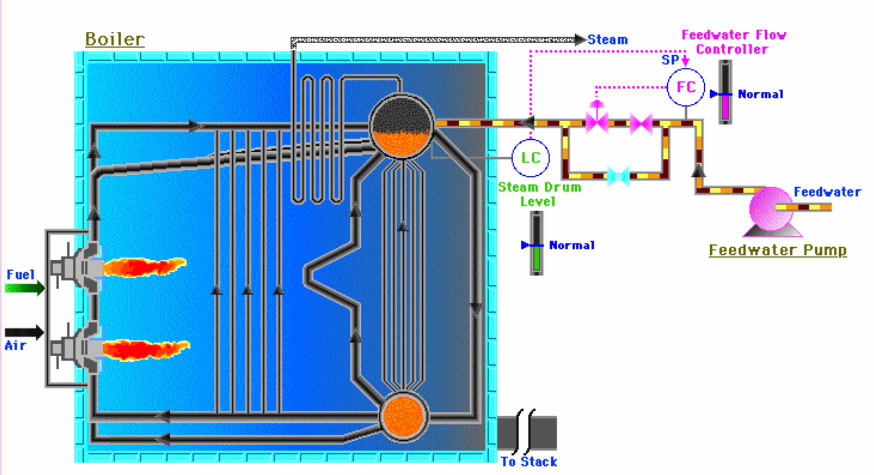

Fig. 8-2: Steam Drum Level Control

Typically, a low steam drum level can be caused by

- Error in level measurement,
- Feed Water Pump failure,
- Feed Water Control Valve failure,
- Leakage in the heating tubes.

Upon detection of low steam drum level the immediate response should be to identify the cause of the problem. For example, if the level transmitter generates a false higher signal, the feed water flow controller reduces the feed water supply to the steam drum. With the reduction in the boiler feed water, the actual steam drum level falls. In this situation the immediate corrective action is to control the drum level manually by manipulating either the control valve or the bypass valve. The feed water flow rate should be controlled manually to match the steam flow rate. Please note that most boilers normally have three steam drum level transmitters. The boiler trip is activated only if two out of three transmitters indicate low level.

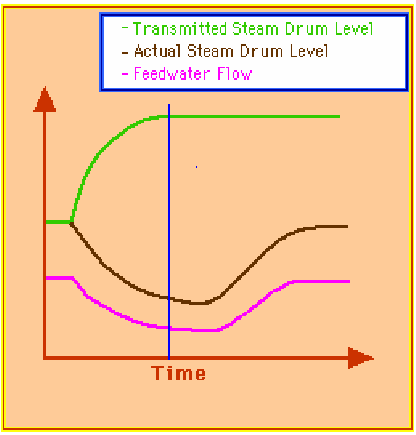

Fig. 8-3: Steam Drum Level on automatic control when transmitter drift occured and manually recovered

If the feed water pump fails, the steam drum level will begin to decrease immediately. A feed water pump failure can be easily identified by a sudden drop in the feed water pump discharge pressure. Upon detection of this problem if a backup feed water pump is available the immediate corrective action is to start the backup pump. Most backup pumps are started automatically upon a reduction of feed water pump discharge pressure. If the autostart logic is not implemented the backup pump should be started manually as soon as possible.

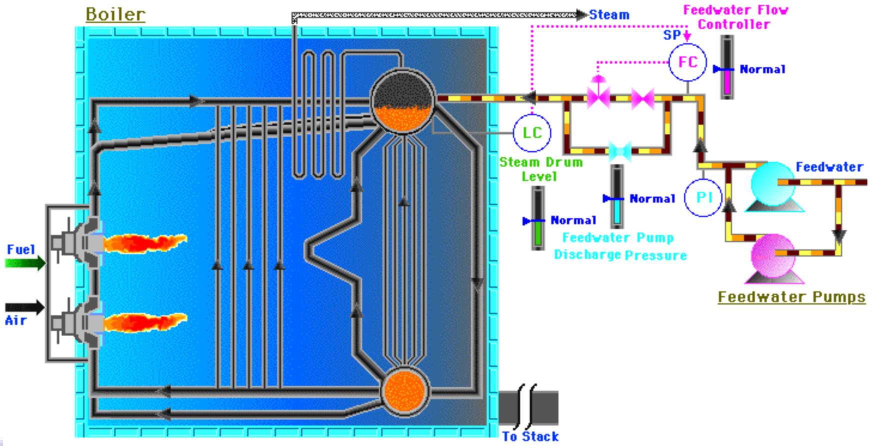

Fig. 8-4: Start-up of backup feedwater pump on low discharge pressure

The recovery action for the low steam drum level should always be gradual. A sudden increase of feed water flow cools the heated area rapidly resulting in a drop in steam pressure which inreases thermal stresses in the heating tubes. Excessive thermal stresses reduce the tube metal strength and increase the possibility of tube rupture in the future.

8.2 Rupture of Heating Tubes

A rupture of heating tubes leads to water leakage in the boiler. The leaked water vaporizes due to intense heat in the boiler and mixes with the flue gas. The flue gas temperature drops immediately. The drum level also drops, but if the leak is minor the level controller can make up. Normally, a rupture in the heating tubes can be easily detected by observing a sudden drop in flue gas temperature, sudden increase in feed water flow, whitish smoke from the stack, abnormal noise or hissing sound, unstable flame in burners or flame out of burners. Upon detection of a heating tube rupture the boiler should be shutdown immediately for repairs. After the shutdown the boiler should be cooled and the water should be drained.

8.3 Flame-out of Burners

Flame-out of burners can occur under many situations, such as

- too little air flow,
- too high air flow,
- rapid changes in the fuel flow,
- very low fuel pressure at the burner inlet.

When the flame-out occurs no combustion takes places at the burner while the fuel continues to flow into the boiler. This fuel partially burns in the firebox due to intense heat and in the presence of flame from other burners. This is an extremely dangerous condition and can lead to an explosion.

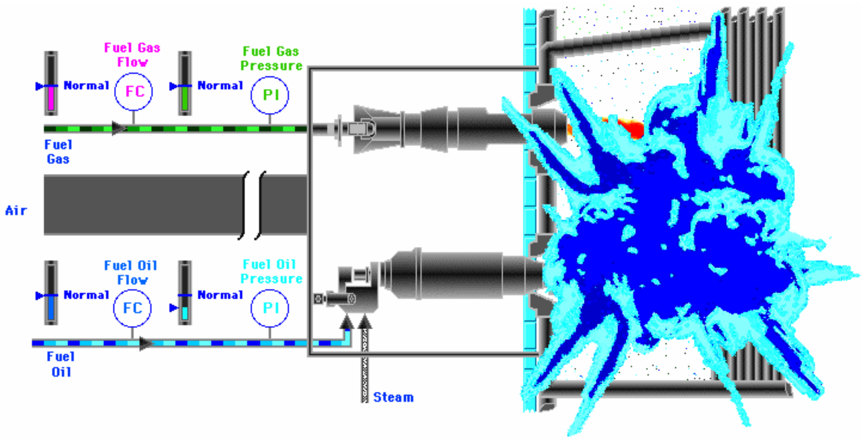

Fig. 8-5: Explosion of Firebox

The immediate corrective action is either to shut down that burner or shut down the entire boiler. Some factors that can possibly lead to a firebox explosion are

- Leakage in the fuel line or the fuel valves,
- unburnt fuel in the firebox,
- difficulty in establishing a stable flame during start-up.

9 Other Operating Considerations

In this chapter we are going to learn about critical parameters that need to be monitored during normal operation of a boiler. The key operating variables of a boiler like steam temperature, pressure etc. are controlled by advanced control strategies. Apart from monitor key operating variables additional conditions need to be monitored regularly, such as combustion condition, water leakage, soot deposits or measurement errors.

9.1 Combustion Condition

The combustion condition of fuel at the burner can be monitored by observing

- Color,
- Shape and
- Position of the flame.

The color of the flame mostly depends on the type of fuel and the combustion condition. The following are some broad characteristics

- for Gas Burners:

Flame Color / Characteristic	*Combustion Condition*
Blue	Proper Combustion
Yellow	Incomplete Combustion due to shortage of air flow.
Blue White	Poor Combustion due to slightly higher air flow.
Longer Flame	Incomplete Combustion due to very low primary air.
Flame lifts off the base	Poor Combustion due to excess primary air.

- for Oil Burners:

Flame Color / Characteristic	*Combustion Condition*
Orange	Proper Combustion
Light Orange	Incomplete Combustion due to slightly higher air or atomizing steam flow.
Red	Incomplete Combustion due to slight shortage of air or atomizing steam flow.
Dark Red	Incomplete Combustion due to shortage of air flow or improper atomization.
Flame lifts off the base	Poor Combustion due to excess primary air.

Normally, the flame condition can be adjusted by manipulating

- the primary air registers or
- the secondary air registers or
- the atomizing steam flow

at the burner.

Sometimes the total air flow rate may have to be changed. Please note that in any manipulation of the air flow it is very important to maintain the oxygen content in the flue gas within an acceptable range.

9.2 Water Leakage

A leakage in the boiler results mainly due to damaged heating tubes and leads to a loss of boiler feed water or steam. A leakage can be easily detected by observing the imbalance between the feed water flow and the steam generated. At the steady state condition the feed water flow rate should be equal to the sum of steam generation rate and the blowdown rate from the drum. A substantial difference between the two quantities may be due to a leakage or an error in measurement.

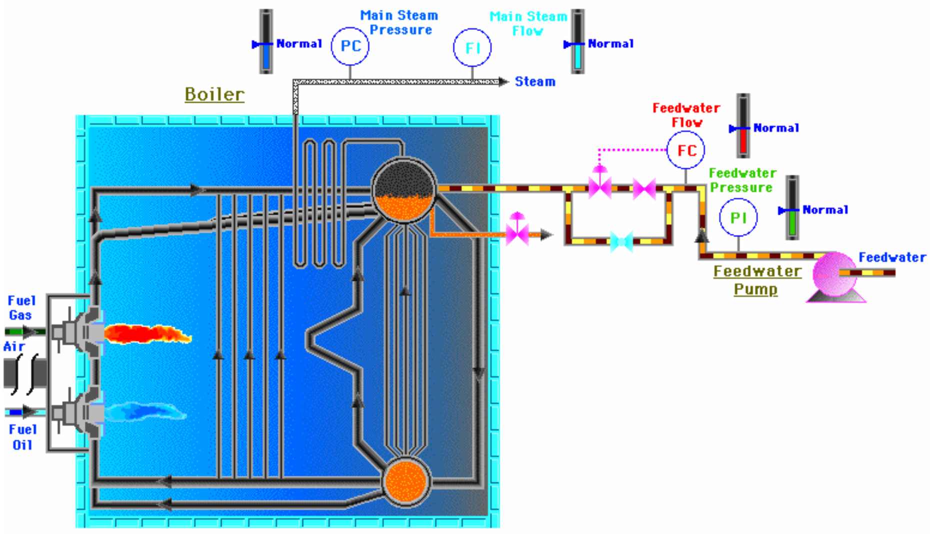

Fig. 9-1: Detection of Feedwater Leakage

In most cases it is possibel to identify the location of the leakage. Let us assume that there is substantial leakage of boiler feed water. If both the feed water flow and the pressure decrease this implies that there is leakage at the upstream of these measurement devices.

On the other hand, if the feed water pressure decreases and feed water flow increases the leakage is more likely to occur at the downstream of the measurement devices.

9.3 Soot Deposits

The carbon from the incomplete combustion of fuel is called soot and it deposits on the heating tubes. Over a period of time the soot deposits build up and reduce the heat transfer through the heating tubes. This results in increased flue gas temperature and leads to a lower boiler efficiency.

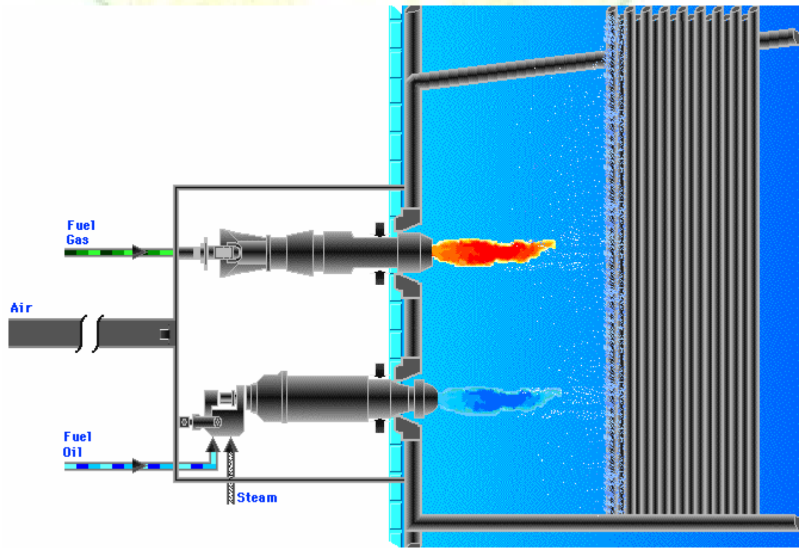

Fig. 9-2: Soot Deposition on Heating Tubes

Soot, if present for a long time, also corrodes the surface of the heating walls by promoting the oxidation on the metal surface. The soot accumulation can be minimized by maintaining proper combustion conditions at the burner. The soot should also be removed periodically to avoid severe reduction in the heat transfer rate. Normally, the soot is removed with a device known as *soot blower*.

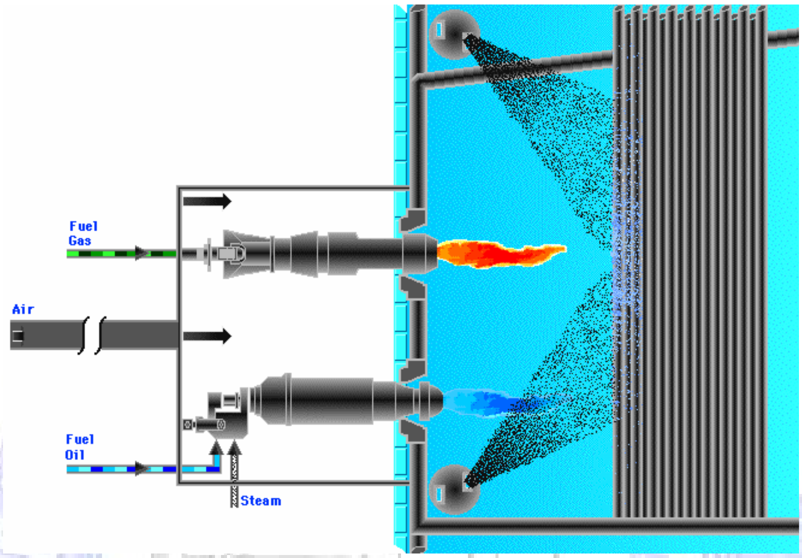

Fig. 9-3: Cleaning of Heating Tubes using Soot Blowers

A boiler has a number of soot blowers and they blow steam or compressed air to remove soot deposits. The soot blowers are placed at various locations, such as the firebox, heating tubes, superheaters etc.. During the soot blowing operation the soot blowers are operated one at a time. The normal practice is to clean the firebox first and then the heating tubes. The operation of soot blowers in the combustion zone can cause severe pulsations due to disturbance in the draft. Hence, during soot blowing operation the combustion air flow rate is increased to minimize the disturbance.

9.4 Measurement Errors

Transmitter drifts constitute the major cause for error in measurements. If the error is associated with a controlled variable the automatic control system acts on the erroneous signal. Depending upon the extent of the error it can lead to either poor control or a major upset.

For example, if the main steam pressure transmitter sends a signal lower than the actual value, the automatic control system acts on this erroneous signal by increasing the fuel. The results in abnormally high steam pressure and sometimes lifts the safety valve. Hence, when any error in the controlled variable is detected, it is advisable to operate the controller manually until the problem is corrected.

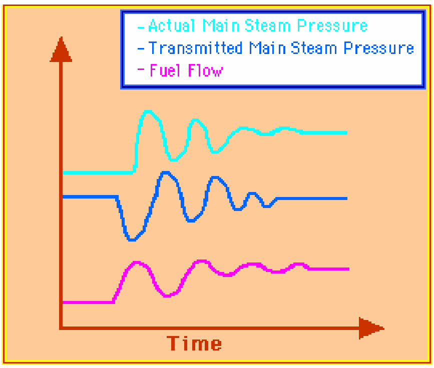

Fig. 9-4: Error in Steam Pressure Measurement

As another example, when the air flow transmitter sends a higher signal than normal, the supply of air to the burners is reduced. Depending upon the extent of the error the air may become dangerously low and may cause poor combustion or flame-out of burners. This can be easily be monitored by observing a sudden decrease in the oxygen level in the oxygen indicator. In such situations the air damper has to be manually operated to maintain the oxygen level and the air flow.

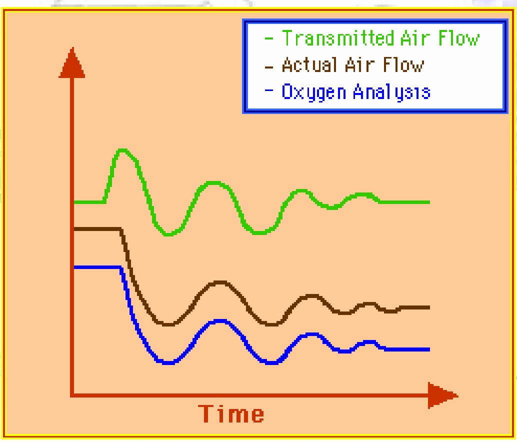

Fig. 9-5: Error in Air Flow Measurement