Introduction to Boiler Combustion

Learning Outcome
*When you complete this module you will be able to:*

Discuss the basic theory of combustion in a boiler and the equipment used to provide proper combustion conditions.

Learning Objectives
*Here is what you will be able to do when you complete each objective:*

1. Describe the principles of combustion, combustion equations and the relationships between theoretical and excess air.

2. Describe the three general classes of boiler fuels.

3. Describe the methods used in the combustion of coal, oil, and gas.

INTRODUCTION

The term "combustion" refers to the burning of a fuel in a boiler furnace in order to produce heat. It is important that the power engineer understands this process because, if the combustion is not carried out in the proper manner, then the fuel will not be completely burned and less heat per kilogram of fuel will be produced. Therefore more fuel than necessary will have to be fed to the furnace with a resulting higher fuel bill. In addition, if the combustion is not carried out in a proper manner, there will be a danger of explosions occurring in the furnace.

In order to understand the basic process of combustion, it is necessary to know what components the various fuels contain and what part these components play in the combustion process.

COMBUSTION

All fuels, whether in solid, liquid or gaseous state are composed of combustible and non-combustible elements. The combustible elements consist of hydrogen, carbon, and sulphur; the non-combustible elements are, in variable quantities, moisture, ash, carbon dioxide, and other trace elements.

Some of the combustible elements may be chemically united, such as hydrogen and carbon, called volatile matter or hydrocarbons. Occasionally in gaseous fuels the carbon is combined with oxygen and denoted as carbon monoxide (CO) which is a combustible gas and could also be produced during an incomplete combustion process.

Moisture (H\textsubscript{2}O) is another example of a combustible element combined with oxygen; two atoms of hydrogen combine with one atom of oxygen forming one molecule of water. The presence of moisture in a fuel, such as coal, may be due to the absorption of moisture from the atmosphere or from hydrogen and oxygen in the fuel being chemically combined prior to combustion.

Theory of Combustion

In the process of combustion, the main combustible elements of the fuel, carbon, hydrogen, and sulphur, combine chemically with oxygen from the air. As a result of this combination, heat is produced. Thus combustion is the rapid oxidation of a fuel whereby large quantities of heat are produced.

To ensure complete combustion of the fuel in the furnace, the following conditions must be fulfilled.
1. Enough air must be supplied to the furnace to provide sufficient oxygen to combine with all the combustible elements of the fuel.

2. The air and the fuel must be thoroughly mixed together so that each particle of fuel can come in contact with the necessary oxygen. This thorough mixing of fuel and air is known as turbulence.

3. The temperature in the furnace must be high enough to ignite the fuel as it enters.

4. The furnace must be large enough to allow sufficient time for the combustion to be completed before the gases strike the cooler areas of the heating surfaces.

The above conditions may be summed up as **enough air** plus **enough time**, **temperature**, and **turbulence**. The last three are often referred to as the three Ts of combustion. In other words, the requirements for proper combustion are the three Ts plus enough air. If poor or no combustion is taking place in a furnace, then one or more of the four conditions is not being met.

**Products of Complete Combustion**

Of the combustible elements in a fuel, carbon forms the greatest percentage. If the combustion is complete, then each atom of carbon will combine with two atoms of oxygen to produce the gas carbon dioxide (CO$_2$) plus heat.

The hydrogen in a fuel will combine with the oxygen to produce water vapour (H$_2$O) plus heat.

The sulphur in the fuel will combine with oxygen to produce the gas sulphur dioxide (SO$_2$) plus heat.

The combustion process can be expressed in simple chemical equations, which represent the combination of these combustible elements with oxygen during complete combustion (Equations 1-3).

1. Carbon + Oxygen $\rightarrow$ Carbon Dioxide  
   \[ C + O_2 \rightarrow CO_2 \]

2. Hydrogen + Oxygen $\rightarrow$ Water Vapour  
   \[ 2H_2 + O_2 \rightarrow 2H_2O \]

3. Sulphur + Oxygen $\rightarrow$ Sulphur Dioxide  
   \[ S + O_2 \rightarrow SO_2 \]
The non-combustible elements of fuel will not combine with oxygen but will form ash or will pass through the furnace unchanged.

**Products of Incomplete Combustion**

If any of the requirements for complete combustion are missing, then the combustible elements will not combine completely with oxygen. Equations 4-7 represent the incomplete combining of oxygen and combustibles.

4. Carbon + Insufficient Oxygen → Carbon monoxide
   
   \[ 2C + O_2 \rightarrow 2CO \]

   Equation 4 shows the formation of carbon monoxide instead of carbon dioxide. This reaction is undesirable because carbon monoxide is a combustible compound and, in passing out of the furnace without burning, it will represent a loss of heating value and a waste of fuel, as well as contributing to pollution. However, if the carbon monoxide combines with more oxygen before leaving the furnace, then its combustion will be complete and carbon dioxide will be formed (Equation 5).

5. Carbon monoxide + Oxygen → Carbon dioxide
   
   \[ 2CO + O_2 \rightarrow 2CO_2 \]

   Equation 6 shows the formation of free hydrogen. This process is undesirable because it is a combustible element, which, if not burned, will represent a waste of fuel and a loss of heating value.

6. Hydrogen + Insufficient oxygen → Water Vapour + Free hydrogen
   
   \[ 3H_2 + O_2 \rightarrow 2H_2O + H_2 \]

   Similarly, the formation of free sulphur (Equation 7) is undesirable because, being combustible, it represents a waste of fuel. In actual practice, the sulphur in a fuel is considered to be an impurity because, although it is a combustible element, it tends to produce corrosive acids in the presence of water. The sulphur dioxide discharged into atmosphere also contributes to air pollution.

7. Sulphur + Insufficient oxygen → Sulphur dioxide + Free sulphur
   
   \[ 2S + O_2 \rightarrow SO_2 + S \]
Combustion Air and Excess Air

Air is basically composed of a mixture of oxygen and nitrogen. The approximate proportions are 21 percent oxygen and 79 percent nitrogen by volume.

The oxygen required for complete combustion must be obtained from the air supplied to the furnace. The amount of air required to supply just enough oxygen for complete combustion is called the theoretical air. In actual practice, however, it is necessary to supply more than this theoretical amount of air in order to make sure that all particles of fuel come in contact with oxygen. The amount of air in excess of the theoretical air is called excess air and is usually expressed as a percentage of the theoretical air.

Example 1:

If the theoretical amount of air required for the complete combustion of 1 kg of coal is 12 kg and if the actual amount of air used in the furnace is 18 kg of air for every kilogram of coal, what is the excess air?

Solution:

The amount of air in excess of 12 kg is 6 kg (18 - 12 = 6). Expressed as a percentage of the theoretical air (12 kg), this would be:

\[
\frac{6}{12} \times 100 = 50\% \quad (\text{Ans.})
\]

The percentage of excess air required for proper combustion of a fuel may vary from 10% to 60% or even higher. The amount required will depend upon:

1. The time available for the fuel to mix with the air before it comes in contact with the relatively cool heating surfaces and is cooled below ignition temperature.

2. How well the fuel and air can be mixed together.

3. The temperature existing within the furnace.

These factors were summarized as time, turbulence, and temperature earlier in this module.

It can be seen, therefore, that a gaseous fuel, such as natural gas, that can easily be mixed with the combustion air will require less excess air than a solid fuel such as coal.
It is desirable to reduce the amount of excess air supplied to the furnace as much as possible since the air is heated to a high temperature in the furnace and, therefore, carries a large amount of heat out through the stack. In addition, the power required for a forced draft fan will decrease if less air is supplied.

On the other hand, if the excess air is reduced too much, then there will be the possibility of incomplete combustion occurring, resulting in the formation of carbon monoxide and free hydrogen as explained previously.

**Flue Gases**

Analyzing the chemical composition of the burnt gases after they leave the furnace enables the operator to ascertain whether complete combustion has been attained. A typical composition of burnt gases, denoted from now on as flue gases, may consist of CO₂, H₂O, SO₂, O₂, N₂ and probably ash in a finely divided state. The presence of oxygen is due to supplying more air than theoretically is required to assure complete combustion.

The nitrogen (N₂) is contained in the combustion air as air by weight is composed of 23% oxygen and 77% nitrogen and in terms of volume 21% oxygen and 79% nitrogen. Nitrogen is actually a waste product because it is heated in the furnace and leaves the chimney at a relatively high temperature. The heat contained in the nitrogen represents a heat loss as it will be lost into the atmosphere. For this reason, the amount of excess air should be kept down to a minimum and the amount required is determined by the following factors:

1. Composition and condition of the fuel fired.
2. Method used for burning the fuel.

Obviously, coal ground to a fine powder will require less excess air than that supplied to the furnace in the form of large particles.

The approximate amount of excess air required for the various firing methods and types of fuels are as follows:

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Firing Method</th>
<th>Excess Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Stoker firing</td>
<td>30-35%</td>
</tr>
<tr>
<td></td>
<td>Pulverized</td>
<td>15-20%</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>Gaseous Fuel</td>
<td></td>
<td>10%</td>
</tr>
</tbody>
</table>
If an insufficient amount of air is supplied, or any other requirement for complete combustion is not met, then this will result in incomplete combustion and will be indicated by CO or, under most adverse conditions, soot (carbon) appearing in the flue gases. This represents a serious waste of fuel and, in addition, the possibility of a furnace explosion exists due to pockets of CO being formed in parts of the furnace.

**Air Supply to Boiler or Furnace Room**

It is extremely important that adequate openings be provided to allow sufficient outside air to enter the boiler room for the satisfactory combustion of the fuel. These openings must be in addition to doors and windows which are usually kept shut in cold weather.

A shortage of combustion air will result in incomplete combustion of the fuel, which, in turn, will cause sooting of heating surfaces, plugging of gas passages, poor heat transfer, increased fuel consumption, and, especially when firing oil or gas, the possibility of a disastrous explosion. A shortage of combustion air can also result in carbon monoxide poisoning to anyone entering the room.

CGA BI49.1, the Installation Code for Natural Gas Burning Appliances and Equipment, specifies standards for the type, location, and size of outside air supply inlets with regard to gas burning equipment of various capacities with natural or mechanical draft. Strict adherence to this code is required.

**FUELS**

Fuels can be classified into three groups:

1. Solid fuel such as coal and wood.
2. Liquid fuel such as fuel oils and gasoline.
3. Gaseous fuel such as natural gas, propane, and butane.

**Coal**

Coal is composed of carbon, hydrogen, oxygen, sulphur, nitrogen, moisture and ash. Of these components only carbon, hydrogen and sulphur are combustible. The hydrogen is combined with some of the carbon to form hydrocarbons. These hydrocarbons are known as volatile material since they pass off as gas when the coal is heated. The rest of the carbon, which is not combined with hydrogen, is referred to as fixed carbon. The sulphur represents a very small percentage of a coal’s composition and, although it is combustible, it is considered an impurity since its combustion product, sulphur dioxide, tends to produce corrosion in the boiler and chimney and also contributes to air pollution.
Wood

Historically, wood, and other natural organic materials, were an important source of boiler fuel. The growth in pulp and paper and wood manufacturing industries, combined with the development of coal, oil and gas (which are more concentrated and transportable sources of chemical energy) led to the decline of wood as a fuel. Nevertheless, the byproducts of wood processing, such as bark, chips, and sawdust, continue to be used as fuel in favourable situations such as pulp and paper production. These materials are often referred to collectively as hog fuel. The use of residual organic materials, like sugar cane stalks, and shells from nuts, as fuels, is also common to the food industries and community waste processing plants. Recently, the term biomass, has been applied collectively to this type of source material.

Fuel Oil

Fuel oils are derived from petroleum. Petroleum, called crude oil in its unrefined state, is a mixture of a large variety of hydrocarbon compounds varying from very light hydrocarbons in the gaseous state, through a range of progressively heavier hydrocarbons in the liquid state to very heavy hydrocarbons in the semi-solid state.

In the refinery, the fractional distillation process is used to separate crude oil into a number of distinguishable groups according to specific characteristics such as boiling point, specific gravity and viscosity. These groups are: gases such as methane and ethane, gasoline, jet fuel, kerosene, diesel fuel, light fuel oils, lubricating oils, heavy oils and residue.

The distinction between these groups is not always sharply defined and they may overlap. For example, the diesel fuel range overlaps the light fuel oil range. This means that some diesel fuels are quite similar in composition and characteristics to light fuel oils. In fact, No. 2 diesel fuel is nearly identical to No. 2 fuel oil, the most widely used oil for packaged firetube boilers.

The main components of fuel oils are carbon and hydrogen combined as hydrocarbons. They also contain small amounts of oxygen, sulphur, nitrogen, and some traces of ash. Fuel oils are classified into grade numbers according to their characteristics such as:

1. Relative Density (specific gravity) - the ratio of the mass of a certain volume of oil to the mass of an equal volume of water.
2. Viscosity - a measure of the internal resistance to flow of the oil.
3. Flash Point - the lowest temperature at which the fuel oil gives off enough vapour to ignite when exposed to an open flame.
The flash point is a good indication of the fire hazard involved in the storage and pumping of the oil. Since the flash point of fuel oils is well above ambient temperatures, they are relatively safe fuels to store, even inside a building.

Table 1 shows the various classes of fuel oil, their application, and the average values of the characteristics discussed above.

<table>
<thead>
<tr>
<th>Commercial Grade No.</th>
<th>Relative Density at 15.5°C (60°F)</th>
<th>Viscosity SSU at 38°C (100°F)</th>
<th>Minimum Flash Point °C (°F)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.815</td>
<td>31</td>
<td>37.8 (100)</td>
<td>Light Domestic</td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>32-39</td>
<td>37.8 (100)</td>
<td>Medium Domestic</td>
</tr>
<tr>
<td>4</td>
<td>0.92</td>
<td>45-120</td>
<td>54 (130)</td>
<td>Light Industrial</td>
</tr>
<tr>
<td>5</td>
<td>0.95</td>
<td>140-700</td>
<td>54 (130)</td>
<td>Medium Industrial</td>
</tr>
<tr>
<td>6</td>
<td>0.98</td>
<td>900 and up</td>
<td>66 (150)</td>
<td>Heavy Industrial</td>
</tr>
</tbody>
</table>

Table 1

Characteristics of Fuel Oil

Grades 1 and 2, often called furnace oils, have a relatively low viscosity and relative density. They do not require heating before being fired in the boiler furnace.

Grade 2 oil is the most popular fuel oil for domestic and small commercial or industrial furnaces and boilers.

Grades 4, 5 and 6 are heavier oils with higher viscosities. They require heating during storage and pumping, and additional heating, usually to about 95°C (203°F), before they can be satisfactorily burned in a furnace.

Fuel oils have certain advantages over coal as a boiler fuel:

1. Less storage space is required.
2. The amount fed to the furnace is more easily controlled.
3. Less handling equipment and labour is required.
4. It burns more cleanly (less residuals) and is efficient to use.
One major disadvantage is that oil is more expensive and less abundant than coal.

Natural Gas

Natural gas is obtained from gas wells drilled in gas-bearing rock formations or as a by-product from oil wells. Processing is usually required to remove any undesirable components before it is piped to the markets. The main components of natural gas supplied to the consumer are the hydrocarbons methane (80-90%) and ethane (10-20%). It also may contain traces of propane, butane, nitrogen, oxygen, carbon dioxide and hydrogen sulphide.

The advantages of natural gas as a boiler fuel are:

1. No ash is produced when gas is burned.
2. Little handling equipment is required.
3. The amount fed to the furnace is easily controlled.
4. It is easily mixed with air.
5. It is very clean - no spills, no mess, no residue.
6. No storage space is required.

Natural gas, however, is more expensive than coal and (in some locales) oil and requires long pipelines for transmission from its source to the heating plant. The relative economics of cost and supply for natural gas and oil will be dependent on a number of factors and will be specific to a given location.

Liquefied Petroleum Gases

Liquefied petroleum gases are petroleum products consisting of light hydrocarbons (butane, propane or a mixture of the two) which are in the gaseous state at atmospheric pressure but can be condensed to form a liquid by the application of moderate pressure. In other words, they are petroleum gases that can be easily liquefied.

As a liquid, the product takes as little as 1/120th of the space it needs as a gas, making it easily stored and transported and then burned as a gas. The liquid is converted to gas by reduction of the pressure and absorption of the latent heat required for evaporation from the surrounding area. The boiling point of butane at atmospheric pressure is 0°C (32°F), that of propane -42°C (-44°F). These gases burn completely and cleanly with a bright flame.

Fuel Heating Value

When a unit amount of fuel is burned completely, the heat produced by this combustion is called the heating value of the fuel. The unit amount can be a mass unit (kilogram or pound) or a volume unit (cubic metre or cubic foot), depending on the type of fuel.
The heating value of a fuel depends primarily on the amount of carbon, hydrogen and sulphur in the fuel.

Typical average heating values for various fuels are listed below in Table 2.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>SI Units</th>
<th>Imp. Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal (bituminous)</td>
<td>25 600 kJ/kg</td>
<td>11 000 Btu/lb</td>
</tr>
<tr>
<td>Fuel Oil (light)</td>
<td>45 360 kJ/kg</td>
<td>19 500 Btu/lb</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>37 260 kJ/m³</td>
<td>1 000 Btu/ft³</td>
</tr>
<tr>
<td>Propane</td>
<td>93 150 kJ/m³</td>
<td>2 500 Btu/ft³</td>
</tr>
<tr>
<td>Butane</td>
<td>122 200 kJ/m³</td>
<td>3 280 Btu/ft³</td>
</tr>
</tbody>
</table>

Table 2
Average Fuel Heating Values

BOILER FIRING

Boiler firing methods vary according to the type of fuel being used; namely solid, liquid, or gaseous. The methods discussed will be for the most commonly used fuels coal, fuel oil and natural gas.

Coal Burning Apparatus

The type of coal burning equipment used depends upon whether the coal is in large particles or powdered form. Large coal particles are used in mechanical stokers in which the coal is moved by mechanical means. Powdered coal is used in pulverized mills in which the coal is carried by air.

1. Mechanical Stokers

Mechanical stokers may be classified into three main types: underfeed, crossfeed, and overfeed.

An underfeed stoker is shown in Fig. 1. In this type, the coal is fed up through the firebed by means of a ram and pusher blocks. The ram is operated by steam, compressed air or oil pressure. The coal fed at the bottom is gradually forced upward to the incandescent layer at the top where it ignites and spills over onto the side grates. The air for combustion is supplied below the grates and passes through openings called tuyeres, which run the length of the firebed on either side.

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As the coal burns, the ashes collect on the grates at each side from where they can be dumped into an ashpit below. The combustion air is supplied by means of draft fans.

**Figure 1**
*Underfed Stoker*

This stoker is particularly adapted to burning coal which is high in volatile content.

Fig. 2 shows the arrangement of a **crossfeed** stoker. This type is also referred to as a chain grate stoker or a bar grate stoker depending upon the construction of the grate surface.

The grate surface consists of a moving endless belt, which extends into the furnace from the boiler front. The coal is fed by gravity onto the front portion of the moving grate. The thickness of the fire and the speed of the grate can be regulated so that the fuel is completely burned by the time it reaches the back of the grate and is dumped into the ashpit. The combustion air is supplied by a draft fan and passes up through the grate to the fuel bed.

**Figure 2**
*Crossfeed Stoker Arrangement*
Fig. 3 shows the overfeed stoker which is also known as the spreader stoker. In this type, the coal is spread over the surface of the grate by means of a revolving rotor having blades or paddles which strike the coal pieces and bat them into the furnace.

![Spreaderc Stoker with Dumping Grates](Fig_3_Spreader_Stoker_with_Dumping_Grates)

The grates shown in Fig. 3 are the power operated dumping type which are arranged so that they can be tilted in order to dump the ash into a pit underneath. Combustion air is supplied under the grates by a draft fan and passes up through openings in the grates to the fuel.

2. Pulverized Coal Mills and Burners

Pulverized coal is coal which has been ground to a fine powder or dust. This finely ground coal is carried by means of air flow through pipes from the grinding mills to the burners in the boiler furnace. Due to the powdered form of the coal, it mixes well with the combustion process. In addition to this advantage, pulverizing the coal allows cheaper grades to be burned satisfactorily and better combustion control is possible with the coal in a powdered rather than a solid form.

Fig. 4 shows a commonly used pulverizer design. In this type the raw coal is fed into a rotating bowl. Spring loaded rolls are held in place inside the bowl and the coal is ground to a fine powder between the rolls and the bowl sides. Hot air enters at the side of the mill and flows upward and across the top of the bowl picking up the powdered coal. This coal-air mixture is drawn by an exhauster fan from the mill and travels to the burners through piping.
The pulverized coal burner is illustrated in Fig. 5. The coal-air mixture from the pulverizer enters and flows through a large central nozzle. The additional air required for combustion, known as secondary air, passes through a housing surrounding the central nozzle and the combustion takes place at the burner throat.
Hog fuel and biomass fuels can be burned either on their own, or in conjunction with coal, oil or gas firing systems. A variety of arrangements have been developed to handle the solid materials, including refractory lined chambers, stationary, travelling, and vibrating grates. The hog fuel may be burned together, or separately, with coal. When burned with oil or gas, these fuels have their own burners, separate from the hog fuel.

**Oil Burners**

Before oil can be burned properly it must be broken up into a fine spray or vapor. This breaking up of the oil is known as atomization and it is necessary in order for the combustion air to mix well with the oil. Heavy oils must be heated to approximately 90°C before they can be atomized while light oils do not require heating.

The air atomizing oil burner shown in Fig. 6 is commonly used in packaged boilers. It uses compressed air at about 103 kPa as atomizing air (also called primary air). This atomizing or primary air mixes with the oil near the burner tip and causes atomization to occur. The secondary air necessary for combustion then mixes with the atomized oil as it leaves the burner.

![Air Atomizing Oil Burner](AM2_fig6.gif)

*Figure 6
Air Atomizing Oil Burner*

The steam atomizing oil burner shown in Fig. 7 is frequently used in boilers larger than the packaged type. Its principle of operation is much the same as the air atomizing burner except that steam is used to produce atomization by coming in contact with the oil before it leaves the burner tip. The combustion air then mixes with the atomized oil as it sprays from the burner.
A mechanical atomizing oil burner is shown in Fig. 8. In this type the oil is pumped under high pressure through slots in a sprayer plate and this produces atomization of the oil. This type of burner is used in both packaged and larger boilers.

The rotary cup oil burner shown in Fig. 9 is often used for larger sized packaged boilers. In this type, the oil is pumped to the inside of a cup which is being rotated at about 3500 r/min by an electric motor. Centrifugal force causes the oil to be thrown off the cup’s rim in a fine spray. Primary air is forced in a whirling motion by a fan into the path of the oil spray. Additional secondary air for combustion is supplied to the oil spray as it leaves the burner.
Oil Burner Maintenance and Operation

If the installation is new, the fuel lines should be thoroughly cleaned by blowing out with compressed air or steam before putting burners into operation. This will prevent dirt and other foreign materials from plugging the small holes and passageways in the burner. Accumulations of water must be kept drained from oil storage tanks.

When oil burners become dirty they should be replaced promptly with clean spare burners. The dirty burners should then be cleaned. When cleaning burners use a clean work area and take care not to damage the delicate parts of the burner. Kerosene or special solvents can be used and compressed air used to blow out the burners. **Be sure to wear goggles when blowing out with compressed air.** After cleaning burners, hang them vertically with the tips immersed in kerosene. When shutting off air or steam atomizing burners, the oil should be shut off first and then the burner blown out with steam or air.

The freedom of movement of louvres or registers should be checked regularly and the linkage lubricated. When the burner is in operation, the registers must be adjusted to give the proper ratio of air to oil. Too little air will produce a dark, heavy smoke while too much air will produce a gray-coloured smoke.

When the boiler is operating at low ratings then the number of burners in service should be reduced in order to maintain adequate oil pressure and thus a stable flame at the burners still in service. When burners are not in use, they should be removed from the furnace otherwise the heat may cause carbon to form within the burner.
Gas Burners

Since gas is already in an atomized condition, there is no necessity for further atomization at the burner. Therefore the main function of the gas burner is to provide for complete and turbulent mixing of the gas and the combustion air.

A type of gas burner often used in packaged firetube boilers is sketched in Fig. 10. Essentially it consists of a tube contained within another tube. Air, blown by a fan, travels through the central tube while the gas is admitted to the annular space between the two tubes. The gas issues from small holes at the end of the annular space while the air passes out through louvres at the end of the central tube. The two mix together and the mixture is given a whirling motion due to the velocity of the air.

![Figure 10](Packaged Boiler Gas Burner)

This type of burner is known as an after-mix or outside mixing type as the gas and air mix together after they leave the burner.

The burner sketched in Fig. 11 is known as a pre-mix type as the gas and some air (primary air) mix together inside the burner itself. The amount of gas entering the burner is controlled by a needle valve and the primary air enters through a controlling shutter at the end of the burner. The two mix together as they pass through a venturi tube. Additional (secondary) air for combustion is supplied as the mixture leaves the tube. This type is used in small installations.
A gas burner suitable for use in a large boiler is shown in Fig. 12. In this ring type burner, gas is supplied to a ring manifold, which contains numerous gas outlet holes. Air is admitted through the register louvres and mixes with the gas leaving the ring holes.
Gas Burner Maintenance and Operation

Gas shut-off cocks should be lubricated periodically with grease and air registers should be checked for freedom of movement and lubricated when necessary. The amount of air admitted to the burner should be adjusted to give a stable flame. The flame color should be blue with yellow tips.

Gas burners should be cleaned whenever the boiler is shut down for routine maintenance or inspection. Carbon deposits can usually be removed with a wire brush and solvents used to cut grease deposits. Burner holes if seriously plugged can be drilled out with a proper sized drill.

The number of burners should be reduced at low loads in order that the remaining burners in service will have adequate gas pressure and a stable flame.

Effects of Combustion on Refractory

The term refractory is used for those materials that can withstand very high temperatures. The most common example of a refractory is firebrick. Earlier designs of boilers used refractory materials for furnace walls but the use of the water-cooled furnace wall in the modern boiler has largely reduced the use of refractories. However refractories are still in use in certain areas in the modern boiler. These areas include burner throats, inspection door opening, combustion chambers and baffles.

The fuel used in the boiler will have an effect on the refractory, some fuels being more destructive than others. Stoker fired units burning coal produce ash slag which will both corrode and erode refractory. Ash clinkers forming on the brickwork will cause portions to break away.

In the case of oil-fired boilers, the refractory may be corroded by the ash from the oil. In addition, if the flame from the burner impinges directly on the brickwork, the surface will tend to break off. If the oil burner is not positioned correctly then carbon will build up on the burner throat refractory.

When natural gas is used as fuel, the refractory problems are usually reduced although, as with the oil burner, impingement of the flame directly on the brickwork surface will cause deterioration.
Fuel Flow Control

Just as proper air flow is necessary to meet the boiler steam flow and pressure requirements, so the fuel flow must also be controlled. The fuel flow rate is generally adjusted to ensure that boiler steam pressure remains constant regardless of steam demand.

Any changes to the fuel flow rate must be matched to corresponding air flow changes in order to maintain stable and efficient combustion conditions. Fuel flow is changed using the following three general methods:

1. Solid fuel - adjustment of primary flow (for pulverized coal), grate or stoker speed.
2. Fuel oil - solenoid valve (on-off or multi-range control) control valve (modulating control)
3. Natural gas - solenoid valve (on-off or multi-range control) control valve (modulating control)

FLUE GAS ANALYSIS

Earlier in this module, we discussed the need for a certain amount of excess air in order to obtain complete combustion of the fuel. We also learned that too much excess air will cause the efficiency of the boiler to drop since the air will carry a large amount of heat out through the stack. To check the amount of excess air the flue gas contains, a sample of the gas is taken and analyzed for CO\(_2\) content.

We know that carbon in the fuel combines with the oxygen in the combustion air to form carbon dioxide (CO\(_2\)). This CO\(_2\) will be part of the total amount of flue gases leaving the boiler. By determining the percentage of CO\(_2\) in the flue gases, we can calculate, or find directly in combustion tables, the amount of excess air supplied. The amount of CO\(_2\) produced per unit amount of fuel burned will be constant but the percentage of CO\(_2\) in the flue gases depends on the amount of air supplied. The higher the amount of excess air, the lower the percentage of CO\(_2\) and vice versa.

The percentage of CO\(_2\) found in the flue gases also depends on the kind of fuel burned, since different fuels contain different amounts of carbon per unit amount of fuel.
Analyzing the flue gas for CO₂ content is a fairly simple procedure, which can be performed by service personnel or a boiler operator provided with the proper equipment. A flue gas analyzer of moderate cost commonly used for heating boilers is the Fyrite analyzers.

The body of the Fyrite analyzer is moulded of a clear, high-strength plastic. It consists of a top and bottom reservoir connected by a center tube (Fig. 13). The bottom of the lower reservoir is sealed off by a synthetic rubber diaphragm, which rests on a perforated metal plate. The upper reservoir is covered by a moulded plastic cap, which contains a double-seated plunger valve.

A spring holds this valve against a seat in the top cap providing a perfect seal, which makes the instrument spill proof in any position. When the valve is fully depressed, it vents the top reservoir to the atmosphere and seals the center tube beneath it. With the valve partially depressed, the entire instrument is open to the atmosphere.

The bottom reservoir is filled with an absorbing fluid, which extends approximately 6 mm into the bore of the center tube when the instrument is held upright. The scale, which is mounted to one side of the center tube, is movable so that before each test the scale may be conveniently adjusted to locate the zero scale division exactly opposite the top of the fluid column in the center tube.
**Testing Procedure**

To perform a test with the analyzers, the metal sampling tube at the end of the rubber hose is inserted into the chimney flue. Then the connector plug at the other end of the rubber hose is pressed down on the spring-loaded valve at the top of the analyzer (Fig. 14(a)). This opens a passage into the top reservoir and seals off the center bore at the same time. By squeezing and releasing the rubber bulb, a sample of the gas is pumped into the top reservoir.

It takes at least 18 bulb strokes to assure that rubber hose and top reservoir are thoroughly purged and filled with the fresh sample. On the last stroke the connector plug is released which automatically returns the valve to its upper position against the top seat. With the valve in this position, 60 mL of the sample are locked in the analyzers and the top is opened to the center bore (Fig. 14(b)).

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**Figure 14**

*Fyrite Testing Procedure*
The analyzer is now turned over forcing the gas sample to bubble through the absorbing solution. The solution will absorb all CO\(_2\) in the gas sample. The analyzer is then turned back upright.

Absorption of CO\(_2\) by the fluid reduces the volume of gas in the analyzer and a slight vacuum will develop. The atmospheric pressure acts on the flexible diaphragm in the lower reservoir in order to equalize the pressure. This forces an amount of liquid up in the center tube equal to the volume of CO\(_2\) absorbed by the liquid (Fig. 14(c)).

If the scale was zeroed as described, the reading corresponding to the top of the fluid column is the percentage of the CO\(_2\) in the sample tested, which in Fig. 14 (c) appears to be 12 percent.

Instead of analyzing the flue gases for CO\(_2\) content to determine the amount of excess air, an analyzer could be used to measure the O\(_2\) content in the gases for the same purpose. Since the O\(_2\) in the excess air is not needed for combustion it will pass through the boiler and form part of the flue gases. A high percentage of excess air will result in a high percentage of O\(_2\) content in the flue gas and, inversely, a low percentage of excess air will show a low percentage of O\(_2\) in the flue gas. The same type of analyzer can be used, however, it should contain a fluid that will absorb O\(_2\) instead of CO\(_2\).

The absorbing fluids used in the analyzer are good for several hundred readings, but they eventually must be replaced. Be sure that the fluids you are using are not at the end of their usable life.

Another common type of flue gas analyzer is the Orsat analyzer, which works on a principle similar to that used by the Fyrite. More recent types of flue gas analyzers are the electronic analyzers which are much cheaper than the Orsat or Fyrite analyzers, and, once calibrated, are reliable and accurate.

With the CO\(_2\) or O\(_2\) content of the flue gas known, the amount of excess air can be found either by calculation or from tables or graphs. Using tables or graphs is the simplest way.

Table 3 shows the percentages of CO\(_2\) and O\(_2\) that can be expected to be found by flue gas analysis for the various percentages of excess air supplied when burning coal, oil or natural gas. If the type of fuel oil or coal used in your boiler is not represented in Table 3, you should be able to obtain equivalent figures for your particular type of fuel by consulting with your local supplier or utility.
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<th>Fuel</th>
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<th>20</th>
<th>30</th>
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<th>60</th>
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</thead>
<tbody>
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<td>16.9</td>
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<td>14.3</td>
<td>13.2</td>
<td>12.2</td>
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<tr>
<td></td>
<td>O₂</td>
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<td>2.0</td>
<td>3.5</td>
<td>5.0</td>
<td>6.1</td>
<td>7.1</td>
<td>8.0</td>
<td>9.4</td>
<td>10.6</td>
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<tr>
<td>Fuel Oil (Light)</td>
<td>CO₂</td>
<td>15.4</td>
<td>13.8</td>
<td>12.6</td>
<td>11.5</td>
<td>10.6</td>
<td>10.0</td>
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<tr>
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<td>9.8</td>
<td>10.9</td>
</tr>
</tbody>
</table>

*Table 3
CO₂ and O₂ Percentages in Flue Gas

Example 2:

After analyzing a sample of flue gas from a gas-fired boiler, the reading on the scale of the analyzer shows a CO₂ content of 9.6%. What is the percentage of excess air being supplied to the boiler?

Solution:

Using Table 3, follow the horizontal CO₂ line for natural gas and see if 9.6% is shown on this line. If it is not shown, the values above and below 9.6 (9.1 and 9.9) must be used to interpolate (i.e. calculate) the approximate value of excess air for a CO₂ percentage of 9.6.

Read the percentage of excess air on top of the vertical column for each of 9.1 and 9.6. In our case that would be:

- 20% when the percentage of CO₂ is 9.9% and
- 30% when the percentage of CO₂ is 9.1%.

These readings show that, in this range, the percentage of CO₂ in the flue gas drops 0.8% when excess air is increased by 10%. This is equivalent to a drop of 0.1% CO₂ for each 1.25% increase in excess air.

Since our reading of 9.6% CO₂ is 0.3% below 9.9% CO₂, the excess air will be:

\[
3 \times 1.25 = 375\% \text{ higher, or}
\]

\[
\text{the excess air} = 20 + 3.75 = 23.75\% \text{ (Ans)}
\]
The results of the analysis should be used as a guide to regulate the air supply so that no more excess air is supplied than is necessary to obtain complete combustion.

The ideal amount of excess air varies for different types of boilers and firing equipment. Boiler operators are advised to consult the boiler manufacturer’s service manual for their particular boiler for the recommended amount of excess air to be supplied to the boiler. Keep in mind that a clean-burning flame together with the correct amount of CO$_2$ in the flue gas are essentials for good combustion.

**Combustion Efficiency (Boiler Efficiency)**

The combustion efficiency indicates what percentage of the heat produced by the combustion of the fuel is actually absorbed by the water in the boiler. Consequently, it also indicates how much of the heat is disappearing up the stack.

A certain amount of heat loss cannot be avoided since the flue gases carry some heat up the stack. The boiler operator can limit this heat loss by keeping the excess air down to the amount required for complete combustion and by keeping the heating surfaces as clean as possible so the maximum amount of heat can be transferred from the flue gases to the water before the gases leave the boiler.

A boiler operator or serviceperson can determine the efficiency of a boiler simply through the use of a combustion efficiency chart (Fig. 15). To use the charts in Fig. 15 two things must be known:

1. The percentage of CO$_2$ in the flue gases leaving the boiler (found by flue gas analysis).

2. The net stack temperature, which is the difference between the temperature of the flue gases leaving the boiler (found by using a thermometer in the boiler stack) and the temperature of the air entering the combustion chamber (found by using a thermometer in the wind box).

By applying this information to the chart pertaining to the fuel used, the efficiency of the boiler can be found.
Figure 15
Combustion Efficiency Charts
Example 3:

The flue gas analysis of an oil-fired boiler shows a 12% CO$_2$ content while the net stack temperature is 275°C (527°F). Find:

(a) the percentage of excess air supplied;
(b) the combustion efficiency of the boiler.

Solution:

(a) Following the CO$_2$ line for fuel oil in Table 3, we find that at 12.6% CO$_2$ excess air is 20%. At 11.5% CO$_2$ excess air is 30%. Thus CO$_2$ content drops 1.1% for a 10% increase in excess air. Since CO$_2$ content is 12%, 0.6% below 12.6%, the excess air increase will be:

$$0.6 / 1.1 \times 10\% = 5.5\% \text{ above } 20\%$$

Thus, the percentage of excess air is 25.5% (Ans).

(b) Using the efficiency chart for oil in Fig. 15, follow the CO$_2$ column for 12% to the intersection with the net stack temperature column and read the efficiency.

Since the 527°F net stack temperature falls between the 500°F and 550°F temperature columns given on the chart, we take the readings at the intersections of both columns. At 12% CO$_2$ content and a 500°F net stack temperature, the efficiency is 81.5%. At 12% CO$_2$ content and a net stack temperature of 550°F, the efficiency is 79.5%. Since our temperature is 527°F, which is almost exactly halfway between 500°F and 550°F, we can use the corresponding efficiency value of 80.5% (halfway between 79.5% and 81.5%) and be very close to the exact value we would get using calculations.

With a 12% CO$_2$ content and a net stack temperature of 527°F, the boiler efficiency will be approximately 80.5% (Ans).

The efficiency charts show us that:

(a) an increase in excess air, resulting in a drop in percent CO$_2$ content in the flue gases, lowers the efficiency of the boiler and, vice-versa, a decrease in excess air results in a higher boiler efficiency.

(b) a rise in net stack temperature at a specific firing rate results in a drop in boiler efficiency, and a drop in net stack temperature will give a higher boiler efficiency.
A rise in net stack temperature can be caused by the heating surfaces fouling up due to scale forming on the waterside or soot and ash deposits on the fireside. It can also be caused by an increase in excess air. Because the extra air increases the total volume of flue gases that have to pass through the boiler during a specific time, the gases must travel faster through the boiler. This results in a lower time of contact between gas and heating surfaces, less heat transferred to the water and hence lower efficiency.