Oxygen (O_2) is one of the most common elements on earth making up 20.9% of our air. Rapid fuel oxidation results in large amounts of heat. Solid or liquid fuels must be changed to a gas before they will burn. Usually heat is required to change liquids or solids into gases. Fuel gases will burn in their normal state if enough air is present.

Most of the 79% of air (that is not oxygen) is nitrogen, with traces of other elements. Nitrogen is considered to be a temperature reducing dilutant that must be present to obtain the oxygen required for combustion.

Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. It also increases the volume of combustion by-products, which then have to travel through the heat exchanger and up the stack faster to allow the introduction of additional fuel air mixture.

This nitrogen also can combine with oxygen (particularly at high flame temperatures) to produce oxides of nitrogen (NO_x), which are toxic pollutants.

Carbon, hydrogen and sulphur in the fuel combine with oxygen in the air to form carbon dioxide, water vapour and sulphur dioxide, releasing 8084 kCal, 28922 kCal & 2224 kCal of heat respectively. Under certain conditions, Carbon may also combine with Oxygen to form Carbon Monoxide, which results in the release of a smaller quantity of heat (2430 kCal/kg of carbon) carbon burned to CO_2 will produce more heat per pound of fuel than when CO or smoke are produced.

$C + O_2 \rightarrow CO_2$ + 8084 kCal/kg of Carbon
$2C + O_2 \rightarrow 2\,CO$ + 2430 kCal/kg of Carbon
$2H_2 + O_2 \rightarrow 2H_2O$ + 28,922 kCal/kg of Hydrogen
$S + O_2 \rightarrow SO_2$ + 2,224 kCal/kg of Sulphur

Each kilogram of CO formed means a loss of 5654 kCal of heat (8084-2430).

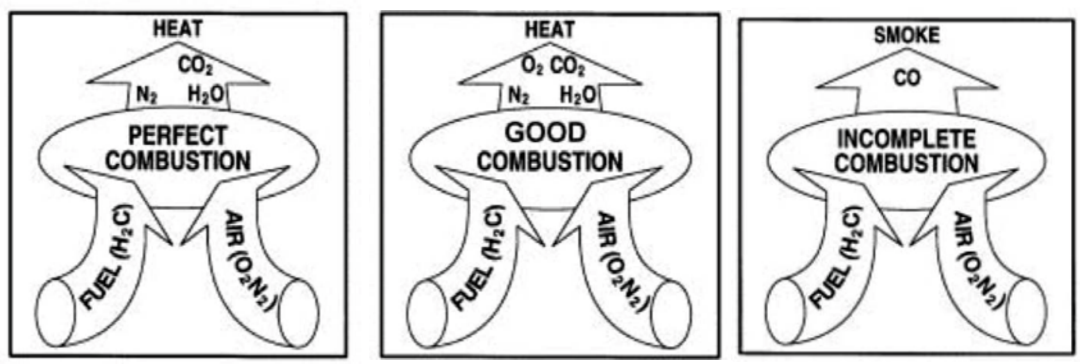
3 T's of Combustion

The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the "three T's" of combustion which are (1) Temperature high enough to ignite and maintain ignition of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time sufficient for complete combustion.

Commonly used fuels like natural gas and propane generally consist of carbon and hydrogen. Water vapor is a by-product of burning hydrogen. This robs heat from the flue gases, which would otherwise be available for more heat transfer.

Natural gas contains more hydrogen and less carbon per kg than fuel oils and as such produces more water vapor. Consequently, more heat will be carried away by exhaust while firing natural gas.

Too much, or too little fuel with the available combustion air may potentially result in unburned fuel and carbon monoxide generation. A very specific amount of O_2 is needed for perfect combustion and some additional (excess) air is required for ensuring complete combustion. However, too much excess air will result in heat and efficiency losses.



Not all of the heat in the fuel are converted to heat and absorbed by the steam generation equipment. Usually all of the hydrogen in the fuel is burned and most boiler fuels, allowable with today's air pollution standards, contain little or no sulfur. So the main challenge in combustion efficiency is directed toward unburned carbon (in the ash or incompletely burned gas), which forms CO instead of CO_2.

1.7 Combustion of Oil

Heating Oil to Correct Viscosity

When atomizing oil, it is necessary to heat it enough to get the desired viscosity. This temperature varies slightly for each grade of oil. The lighter oils do not usually require pre-heating. Typical viscosity at the burner tip (for LAP, MAP & HAP burners) for furnace oil should be 100 Redwood seconds-1 which would require heating the oil to about 105 ^{o}C.

Stoichiometric Combustion

The efficiency of a boiler or furnace depends on efficiency of the combustion system. The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur etc. This amount of air is called stoichiometric air. For ideal combustion process for burning one kg of a typical fuel oil containing 86% Carbon, 12% Hydrogen, 2% Sulphur, theoretically required quantity of air is 14.1 kg. This is the minimum air that would be required if mixing of fuel and air by the burner and combustion is perfect. The combustion products are primarily Carbon Dioxide (CO_2), water vapor (H_2 O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air.

After surrendering useful heat in the heat absorption area of a furnace or boiler, the combustion products or fuel gases leave the system through the chimney, carrying away a significant quantity of heat with them.

Calculation of Stoichiometric Air

The specifications of furnace oil from lab analysis is given below:

Constituents	% By weight
Carbon	85.9
Hydrogen	12
Oxygen	0.7
Nitrogen	0.5
Sulphur	0.5
H_2O	0.35
Ash	0.05

GCV of fuel : 10880 kCal/kg

Calculation for Requirement of Theoretical Amount of Air

Considering a sample of 100 kg of furnace oil. The chemical reactions are:

Element	Molecular Weight kg / kg mole
C	12
O_2	32
H	2
S	32
N_2	28
CO_2	44
SO_2	64
H_2O	18

$$C + O_2 \rightarrow CO_2$$
$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$
$$S + O_2 \rightarrow SO_2$$

Constituents of fuel

$$C + O_2 \rightarrow CO_2$$
$$12 + 32 \rightarrow 44$$

12 kg of carbon requires 32 kg of oxygen to form 44 kg of carbon dioxide therefore 1 kg of carbon requires 32/12 kg i.e 2.67 kg of oxygen

$(85.9)\ C + (85.9 \times 2.67)\ O_2 \longrightarrow 315.25\ CO_2$

$2H_2 + O_2 \longrightarrow 2H_2O$
$4 + 32 \longrightarrow 36$

4 kg of hydrogen requires 32 kg of oxygen to form 36 kg of water, therefore 1 kg of hydrogen requires 32/4 kg i.e 8 kg of oxygen

$(12)\ H_2 + (12 \times 8)\ O_2 \longrightarrow (12 \times 9)\ H_2O$

$S + O_2 \longrightarrow SO_2$
$32 + 32 \longrightarrow 64$

32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide, therefore 1 kg of sulphur requires 32/32 kg i.e 1 kg of oxygen

$(0.5)\ S + (0.5 \times 1)\ O_2 \longrightarrow 1.0\ SO_2$

Total Oxygen required (229.07+96+0.5) = 325.57 kg

Oxygen already present in 100 kg fuel (given) = 0.7 kg

Additional Oxygen Required = 325.57 – 0.7
= 324.87 kg

Therefore quantity of dry air reqd. (air contains 23% oxygen by wt.) = (324.87) / 0.23
= 1412.45 kg of air

Theoretical Air required = (1412.45) / 100
= 14.12 kg of air / kg of fuel

Calculation of theoretical CO_2 content in flue gases

Nitrogen in flue gas = 1412.45 – 324.87
= 1087.58 kg

Theoretical CO_2% in dry flue gas by volume is calculated as below :

Moles of CO_2 in flue gas = (314.97) / 44 = 7.16

Moles of N_2 in flue gas = (1087.58) / 28 = 38.84
Moles of SO_2 in flue gas = 1/64 = 0.016

$$Theoritical\ CO_2\%\ by\ volume = \frac{Moles\ of\ CO_2}{Total\ moles\ (dry)}\ x\ 100$$

$$= \frac{7.16}{7.16+38.84+0.016}\ x\ 100$$

$$= 15.5\ \%$$

Calculation of constituents of flue gas with excess air

% CO_2 measured in flue gas = 10% (measured)

$$\%\ Excess\ air = \left(\frac{Theoritical\ CO_2\%}{Actual\ CO_2\%} - 1\right) x\ 100$$

$$\%\ Excess\ air = \left(\frac{15.5}{10} - 1\right) x\ 100\ = 55\%$$

Theoretical air required for 100 kg of fuel burnt	=	1412.45 kg
Total quantity. of air supply required with 55% excess air	=	1412.45 X 1.55
	=	2189.30 kg
Excess air quantity	=	2189.30 – 1412.45
	=	776.85 kg.
O_2	=	776.85 X 0.23
	=	178.68
N_2	=	776.85 - 178.68
	=	598.17 kg

The final constitution of flue gas with 55% excess air for every 100 kg fuel.

CO_2 = 314.97 kg

H_2O = 108.00 kg

SO_2 = 1 kg

O_2 = 178.68 kg

$$N_2 = 1087.58 + 598.17$$
$$= 1685.75 \text{ kg}$$

Calculation of theoretical CO_2% in dry flue gas by volume

Moles of CO_2 in flue gas = 314.97/44 = 7.16
Moles of SO_2 in flue gas = 1/64 = 0.016
Moles of O_2 in flue gas = 178.68 / 32 = 5.58
Moles of N_2 in flue gas = 1685.75 / 28 = 60.20

$$Theoritical\, CO_2\%\, by\, volume = \frac{Moles\ of\ CO_2}{Total\, moles\,(dry)}\ x\,100$$

$$= \frac{7.16}{7.16 + 0.016 + 5.58 + 60.20}\ x\,100$$

$$= \frac{7.16}{72.956}\ x\,100 = 10\%$$

$$\text{Theoretical } O_2\% \text{ by volume} = \frac{5.58\,x 100}{72.956}\ x\,100 = 7.5\%$$

Optimizing Excess Air and Combustion

For complete combustion of every one kg of fuel oil 14.1 kg of air is needed. In practice, mixing is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel oil. If too much air than what is required for completing combustion were allowed to enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses. Less air would lead to the incomplete combustion and smoke. Hence, there is an optimum excess air level for each type of fuel.

Control of Air and Analysis of Flue Gas

Thus in actual practice, the amount of combustion air required will be much higher than optimally needed. Therefore some of the air gets heated in the furnace boiler and leaves through the stack without participating in the combustion

Chemical analysis of the gases is an objective method that helps in achieving finer air control. By measuring carbon dioxide (CO_2) or oxygen (O_2) in flue gases by continuous recording instruments or Orsat apparatus or portable fyrite, the excess air level as well as stack losses can be estimated with the graph as shown in Figure 1.2 and Figure 1.3. The excess air to be supplied depends on the type of fuel and the firing system. For optimum combustion of fuel oil, the CO_2 or O_2 in flue gases should be maintained at 14 -15% in case of CO_2 and 2-3% in case of O_2.

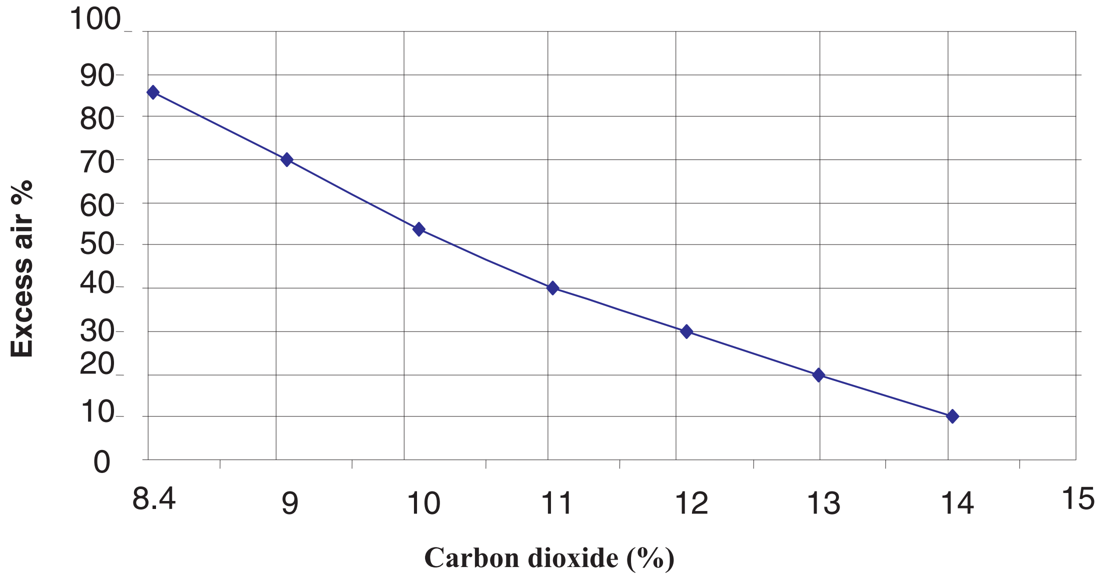


Figure 1.2 Relation Between CO_2 and Excess Air for Fuel Oil

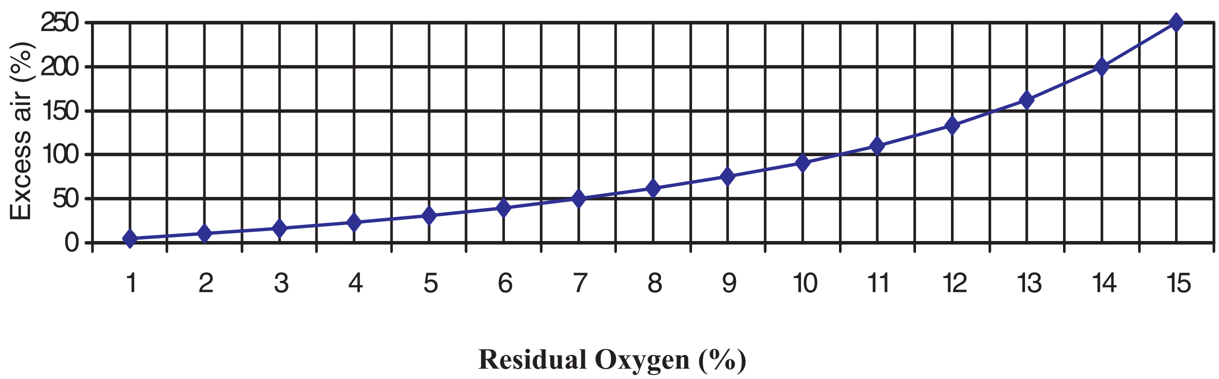


Figure 1.3 Relation between Residual Oxygen and Excess Air

Oil Firing Burners

The burner is the principal device for the firing of fuel. The primary function of burner is to atomise fuel to millions of small droplets so that the surface area of the fuel is increased enabling intimate contact with oxygen in air. The finer the fuel droplets are atomised, more readily will the particles come in contact with the oxygen in the air and burn.

Normally, atomisation is carried out by primary air and completion of combustion is ensured by secondary air. Burners for fuel oil can be classified on the basis of the technique to prepare the fuel for burning i.e. atomisation.

Figure 1.4 shows a simplified burner head. The air is brought into the head by means of a forced draft blower or fan. The fuel is metered into the head through a series of valves. In order to get proper combustion, the air molecules must be thoroughly mixed with the fuel molecules before they actually burn. The air in the center is the primary air used for atomization and the one surrounding is the secondary air which ensures complete combustion.

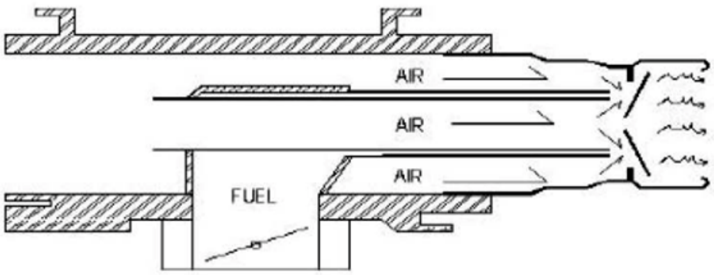


Figure 1.4 Burner Head

The mixing is achieved by burner parts designed to create high turbulence. If insufficient turbulence is produced by the burner, the combustion will be incomplete and samples taken at the stack will reveal carbon monoxide as evidence.

Since the velocity of air affects the turbulence, it becomes harder and harder to get good fuel and air mixing at higher turndown ratios since the air amount is reduced. Towards the highest turndown ratios of any burner, it becomes necessary to increase the excess air amounts to obtain enough turbulence to get proper mixing. The better burner design will be one that is able to properly mix the air and fuel at the lowest possible air flow or excess air.

An important aspect to be considered in selection of burner is **turndown ratio**. Turndown ratio is the relationship between the maximum and minimum fuel input without affecting the excess air level. For example, a burner whose maximum input is 250,000 kCal and minimum rate is 50,000 kCal, has a 'Turn-Down Ratio' of 5 to 1.

1.8 Combustion of Coal

Features of coal combustion

1 kg of coal will typically require 7-8 kg of air depending upon the carbon, hydrogen, nitrogen, oxygen and sulphur content for complete combustion. This air is also known as theoretical or stochiometric air.

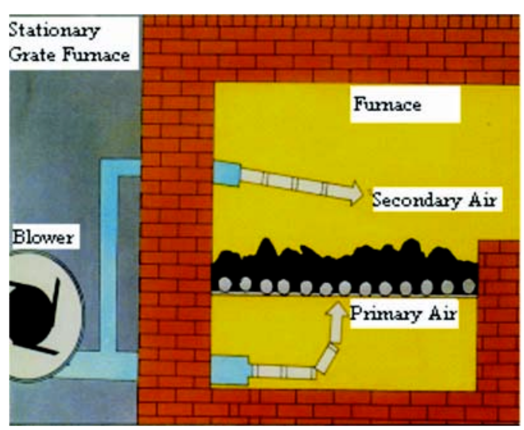


Figure 1.5 Coal Combustion

If for any reason the air supplied is inadequate, the combustion will be incomplete. The result is poor generation of heat with some portions of carbon remaining unburnt (black smoke) and forming carbon monoxide instead of carbon dioxides.

As in the case of oil, coal cannot be burnt with stochiometric quantity of air. Complete combustion is not achieved unless an excess of air is supplied.

The excess air required for coal combustion depends on the type of coal firing equipment. Hand fired boilers use large lumps of coal and hence need very high excess air. Stoker fired boilers as shown in the Figure 1.5 use sized coal and hence requires less excess air. Also in these systems primary air is supplied below the grate and secondary air is supplied over the grate to ensure complete combustion.

Fluidised bed combustion in which turbulence is created leads to intimate mixing of air and fuel resulting in further reduction of excess air. The pulverized fuel firing in which powdered coal is fired has the minimum excess air due to high surface area of coal ensuring complete combustion.

Clinker formation

Clinker is a mass of rough, hard, slag-like material formed during combustion of coal due to low fusion temperature of ash present in coal. Presence of silica, calcium oxide, magnesium oxides etc. in ash lead to a low fusion temperature. Typically Indian coals contain ash fusion temperature as low as 1100 ^{o}C. Once clinker is formed, it has a tendency to grow. Clinker will stick to a hot surface rather than a cold one and to a rough surface rather than a smooth one.

1.9 Combustion of Gas

Combustion Characteristics of Natural Gas

The stoichiometric ratio for natural gas (and most gaseous fuels) is normally indicated by volume. The air to natural gas (stoichiometric) ratio by volume for complete combustion vary between 9.5:1 to 10:1

Natural gas is essentially pure methane, CH_4. Its combustion can be represented as follows:

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

So for every 16 kgs of methane that are consumed, 44 kgs of carbon dioxide are produced. (Remember that the atomic weights of carbon, oxygen and hydrogen are 12, 16 and 1, respectively.)

Methane burns, when mixed with the proper amount of air and heated to the combustion temperature. Figure 1.6 shows the process with the amount of air and fuel required for perfect combustion.

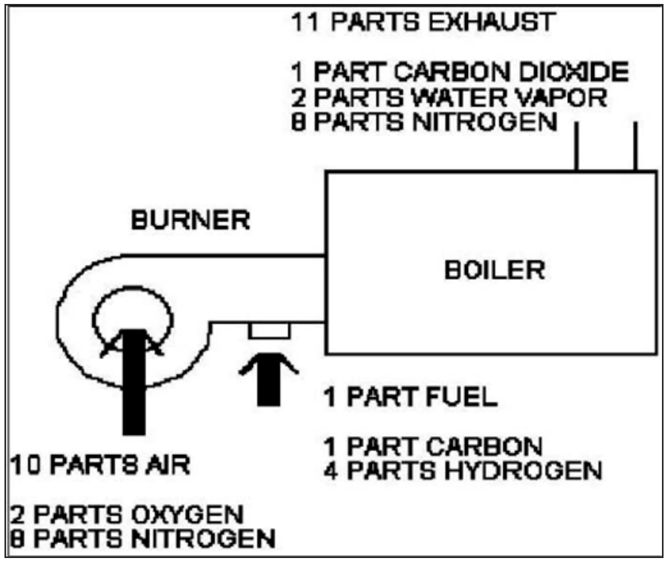


Figure 1.6 Combustion of Natural Gas

Low-And High-Pressure Gas Burners.

The important thing in all gas-burning devices is a correct air-and-gas mixture at the burner tip. Low-pressure burners (Figure 1.7), using gas at a pressure less than 0.15 kg/cm^2 (2 psi), are usually of the multi-jet type, in which gas from a manifold is supplied to a number of small single jets, or circular rows of small jets, centered in or discharging around the inner circumference of circular air openings in a block of some heat-resisting material. The whole is encased in a rectangular cast-iron box, built into the boiler setting and having louver doors front to regulate the air supply. Draft may be natural, induced, or forced.

Figure 1.7 Low Pressure Gas Burner

In a high-pressure gas mixer (Figure 1.8), the energy of the gas jet draws air into the mixing chamber and delivers a correctly proportioned mixture to the burner. When the regulating valve is opened, gas flows through a small nozzle into a venturi tube (a tube with a contracted section). Entrainment of air with high-velocity gas in the narrow venturi section draws air in through large openings in the end. The gas-air mixture is piped to a burner. The gas-burner tip may be in a variety of forms. In a sealed-in tip type, the proper gas-air mixture is piped to the burner, and no additional air is drawn in around the burner tip. Size of the air

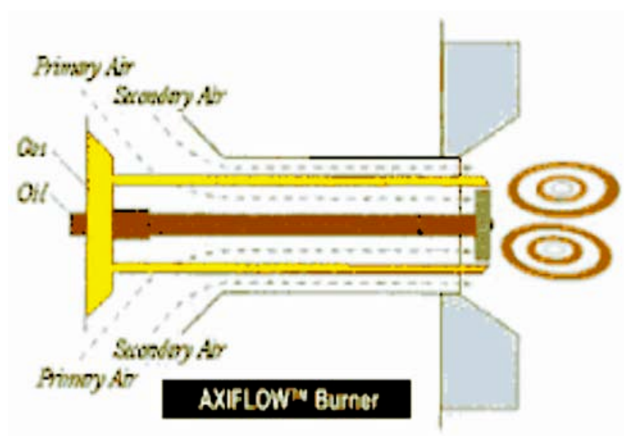


Figure 1.8 High Pressure Gas Mixer

openings in the venturi tube end is increased or decreased by turning a revolving shutter, which can be locked in any desired position. Excess air levels in natural gas burner are in the order of 5%.

1.10 Combustion of Biomass

Biomass can be converted into energy (heat or electricity) or energy carriers (charcoal, oil, or gas) using both thermochemical and biochemical conversion technologies. Combustion is the most developed and most frequently applied process used for solid biomass fuels because of its low costs and high reliability.

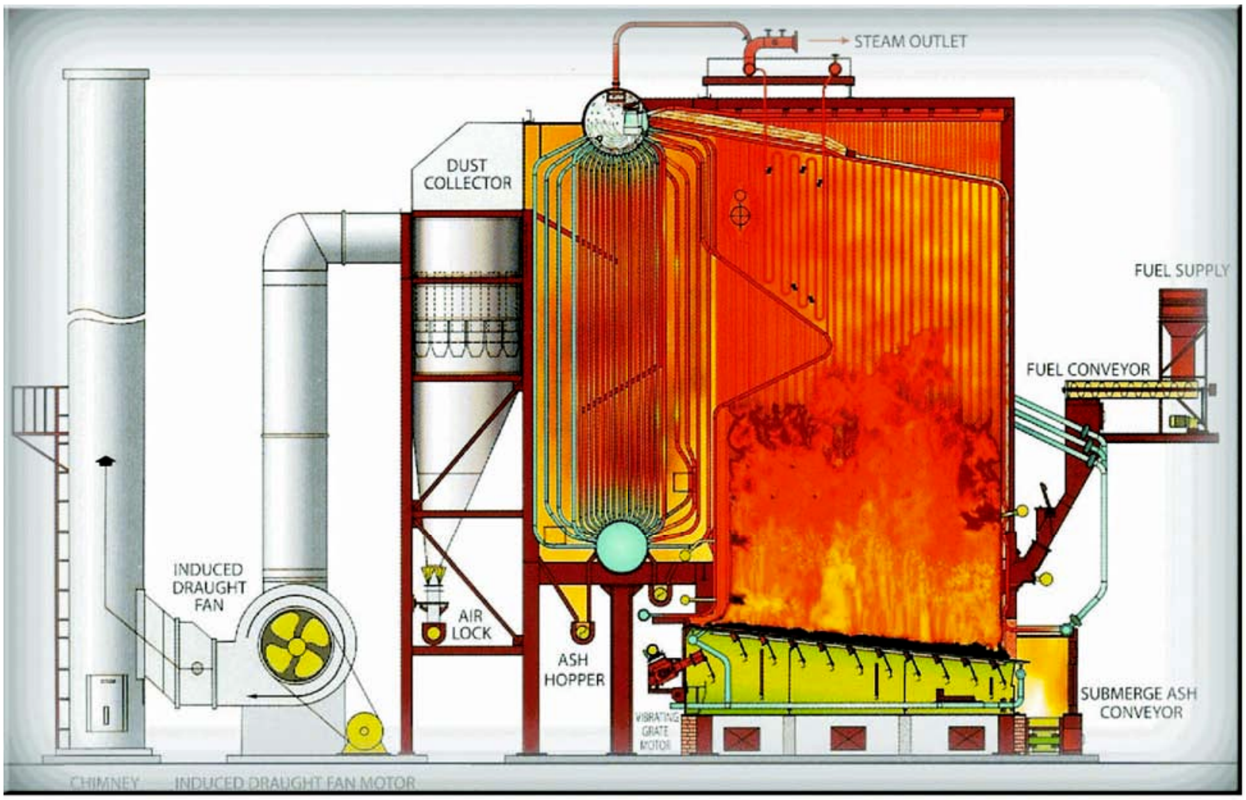


Figure 1.9 Biomass Combustion in a Boiler

During combustion, the biomass first loses its moisture at temperatures up to 100°C, using heat from other particles that release their heat value. As the dried particle heats up, volatile gases containing hydrocarbons, CO, CH_4 and other gaseous components are released. In a combustion process, these gases contribute about 70% of the heating value of the biomass. Finally, char oxidises and ash remains. The combustion installation needs to be properly designed for a specific fuel type in order to guarantee adequate combustion quality and low emissions.

The characteristics and quality of biomass as a fuel depend on the kind of biomass and the pre-treatment technologies applied. For example, the moisture content of the fuel as fed into the furnace may vary from 25 - 55% (on a wet weight basis) for bark and sawmill by-products, and be less than 10% (on a wet weight basis) for pellets. Also, the ash sintering temperatures of biofuels used cover a wide range (800 to 1200°C), as do particle shapes and sizes.

In order to reduce its moisture content, freshly harvested wood is often left outside for a number of weeks before it is chipped and fed to a combustion plant.

Different biomass combustion systems are available for industrial purposes. Broadly, they can be defined as fixed-bed combustion, fluidised bed combustion, and dust combustion.

Fixed-bed combustion

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, where drying, gasification, and charcoal combustion take place in consecutive stages. The combustible gases are burned in a separate combustion zone using secondary air. Grate furnaces are appropriate for burning biomass fuels with high moisture content, different particle sizes, and high ash content. The design and control of the grate are aimed at guaranteeing smooth transportation and even distribution of the fuel and a homogeneous primary air supply over the whole grate surface. Irregular air supply may cause slagging, and higher amounts of fly ash, and may increase the oxygen needed for complete combustion. Load changes can be achieved more easily and quickly than in grate furnaces because there is better control of the fuel supply.

Fluidised bed combustion

In a fluidised bed, biomass fuel is burned in a self-mixing suspension of gas and solid bed material (usually silica sand and dolomite) in which air for combustion enters from below. Depending on the fluidisation velocity, bubbling and circulating fluidised bed combustion can be distinguished.

The intense heat transfer and mixing provide good conditions for complete combustion with low excess air demand. The low excess air amounts required reduce the flue gas volume flow and increase combustion efficiency. Fluid bed combustion plants are of special interest for largescale applications (normally exceeding 30 MWth). For smaller plants, fixed bed systems are usually more cost-effective. One disadvantage is the high dust loads in the flue gas, which make efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new bed material.

Dust combustion

Dust combustion is suitable for fuels available as small, dry particles such as wood dust. A mixture of fuel and primary combustion air is injected into the combustion chamber. Combustion takes place while the fuel is in suspension; the transportation air is used as primary air. Gas burnout is achieved after secondary air addition. An auxiliary burner is used to start the furnace. When the combustion temperature reaches a certain value, biomass injection starts and the auxiliary burner is shut down. Due to the explosion-like gasification process of the biomass particles, careful fuel feeding is essential. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and efficient load control can be achieved. Since the fuel and air are well-mixed, only a small amount of excess air is required. This results in high combustion efficiencies.

1.11 Draft System

The function of draft in a combustion system is to exhaust the products of combustion into the atmosphere. The draft systems can be classified into two types namely Natural and Mechanical Draft.

Natural Draft : It is the draft produced by a chimney alone. It is caused by the difference in weight between the column of hot gas inside the chimney and column of outside air of the same height and cross section. Being much lighter than outside air, chimney flue gas tends to rise, and the heavier outside air flows in through the ash pit to take its place. It is usually controlled by hand-operated dampers in the chimney and breeching connecting the boiler to the chimney. Here no fans or blowers are used. The products of combustion are discharged at such a height that it will not be a nuisance to the surrounding community.

Mechanical Draft : It is the draft artificially produced by fans. Three basic types of draft systems available are:

Balanced Draft : Forced-draft (F-D) fan (blower) pushes air into the furnace and an induced-draft (I-D) fan draws gases into the chimney thereby providing draft to remove the gases from the boiler. Here the pressure is maintained between 0.05 to 0.10 in. of water gauge below atmospheric pressure in the case of boilers and slightly positive for reheating and heat treatment furnaces.

Induced Draft : An induced-draft fan draws enough draft for flow into the furnace, causing the products of combustion to discharge to atmosphere. Here the furnace is kept at a slight negative pressure below the atmospheric pressure so that combustion air flows through the system.

Forced Draft : The Forced draft system uses a fan to deliver the air to the furnace, forcing combustion products to flow through the unit and up the stack.

1.12 Combustion Controls

Combustion controls assist the burner in regulation of fuel supply, air supply, (fuel to air ratio), and removal of gases of combustion to achieve optimum boiler efficiency. The amount of fuel supplied to the burner must be in proportion to the steam pressure and the quantity of steam required. The combustion controls are also necessary as safety device to ensure that the boiler operates safely.

Various types of combustion controls in use are:

ON/OFF Control

The simplest control, ON/OFF control means that either the burner is firing at full rate or it is OFF. This type of control is limited to small boilers.

High/Low/OFF Control

Slightly more complex is HIGH/LOW/OFF system where the burner has two firing rates. The burner operates at slower firing rate and then switches to full firing as needed. Burner can also revert to low firing position at reduced load. This control is fitted to medium sized boilers.

Modulating Control

The modulating control operates on the principle of matching the steam pressure demand by altering the firing rate over the entire operating range of the boiler. Modulating motors use conventional mechanical linkage or electric valves to regulate the primary air, secondary air, and fuel supplied to the burner. Full modulation means that boiler keeps firing, and fuel and air are carefully matched over the whole firing range to maximize thermal efficiency.

QUESTIONS	
Objective Type Questions	
1.	Which fuel requires the lowest amount of excess air for combustion? a) furnace oil b) LDO c) coal d) natural gas
2.	Which fuel requires maximum air for stoichiometric combustion? a) butane b) propane c) hydrogen d) coal
3.	How many kg of CO_2 are produced in complete combustion of 16 kg of methane? a) 42 b) 44 c) 16 d) none of the above
4.	Which agro-residue has the lowest gross calorific value? a) deoiled Bran b) paddy husk c) saw dust d) coconut shell
5.	Which among the following releases the most energy per kg on complete combustion? a) carbon b) sulphur c) nitrogen d) hydrogen
6.	Which among the following is most viscous fluid? a) furnace oil b) HSD c) kerosene d) water
7.	The content of solid left in the oven after volatile matter is distilled off, while analysing the composition of coal in a laboratory is ___. a) only sulphur b) only moisture c) only ash d) mix of fixed carbon and ash
8.	Which is the best suited pump for pumping LSHS? a) vertical turbine pump b) centrifugal pump c) diaphragm pump d) gear pump
9.	Oxygen percentage (by volume) measurement in flue gas can be done by using: a) ultrasonic tester b) potassium oxide probe c) copper tubes d) zirconium oxide probe
10.	For complete combustion of every kg of FO firing, the approximate theoretical quantity of air required is: a) 14 kg b) 18 kg c) 21 kg d) 10 kg
Short Type Questions	
S-1	Explain why natural gas requires least amount of excess air?
S-2	What is volatile matter and what is its significance?
S-3	The measured CO_2 is 8% in an oil fired boiler flue gas. Theoretical CO_2 content for the fuel fired is 16%. Estimate the %excess air level?
S-4	One kg of wood contains 20% moisture and 5% hydrogen by weight. How much water is evaporated during complete combustion of one kg of wood?

S-5	What is the difference between Gross calorific value (GCV) and Net calorific value (NCV)?
	Long Type Questions
L-1	What is draft in combustion system? Explain briefly the different types of draft systems
L-2	i) State the stoichiometric combustion equation for Methane. ii) How many kg of carbon dioxide is generated by complete combustion of 1 kg of Methane? iii) How many kg of water is generated by complete combustion of 1 kg of Methane?

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