1. FUELS AND COMBUSTION

Syllabus
Introduction to Fuels, Properties of Fuel oil, Coal and Gas, Storage, handling and preparation of fuels, Principles of Combustion, Combustion of Oil, Coal, and Gas

This chapter is a prelude to boilers and furnaces

1.1 Introduction to Fuels

The various types of fuels like liquid, solid and gaseous fuels are available for firing in boilers, furnaces and other combustion equipments. The selection of right type of fuel depends on various factors such as availability, storage, handling, pollution and landed cost of fuel.

The knowledge of the fuel properties helps in selecting the right fuel for the right purpose and efficient use of the fuel. The following characteristics, determined by laboratory tests, are generally used for assessing the nature and quality of fuels.

1.2 Properties of Liquid Fuels

Liquid fuels like furnace oil and LSHS are predominantly used in industrial application. The various properties of liquid fuels are given below.

Density

This is defined as the ratio of the mass of the fuel to the volume of the fuel at a reference temperature of 15°C. Density is measured by an instrument called hydrometer. The knowledge of density is useful for quantity calculations and assessing ignition quality. The unit of density is kg/m^3.

Specific gravity

This is defined as the ratio of the weight of a given volume of oil to the weight of the same volume of water at a given temperature. The density of fuel, relative to water, is called specific gravity. The specific gravity of water is defined as 1. Since specific gravity is a ratio, it has no units. The measurement of specific gravity is generally made by a hydrometer.

Specific gravity is used in calculations involving weights and volumes. The specific gravity of various fuel oils are given in Table 1.1

TABLE 1.1 SPECIFIC GRAVITY OF VARIOUS FUEL OILS

Fuel Oil	**L.D.O** Light Diesel Oil	**Furnace oil**	**L.S.H.S** Low Sulphur Heavy Stock
Specific Gravity	0.85-0.87	0.89-0.95	0.88-0.98

Viscosity

The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity depends on temperature and decreases as the temperature increases. Any numerical value for viscosity has no meaning unless the temperature is also specified. Viscosity is measured in Stokes / Centistokes. Sometimes viscosity is also quoted in Engler, Saybolt or Redwood. Each type of oil has its own temperature - viscosity relationship. The measurement of viscosity is made with an instrument called Viscometer.

Viscosity is the most important characteristic in the storage and use of fuel oil. It influences the degree of pre-heat required for handling, storage and satisfactory atomization. If the oil is too viscous, it may become difficult to pump, hard to light the burner, and tough to operate. Poor atomization may result in the formation of carbon deposits on the burner tips or on the walls. Therefore pre-heating is necessary for proper atomization.

Flash Point

The flash point of a fuel is the lowest temperature at which the fuel can be heated so that the vapour gives off flashes momentarily when an open flame is passed over it. Flash point for furnace oil is 66°C.

Pour Point

The pour point of a fuel is the lowest temperature at which it will pour or flow when cooled under prescribed conditions. It is a very rough indication of the lowest temperature at which fuel oil is readily pumpable.

Specific Heat

Specific heat is the amount of kCals needed to raise the temperature of 1 kg of oil by 1°C. The unit of specific heat is kCal/kg°C. It varies from 0.22 to 0.28 depending on the oil specific gravity. The specific heat determines how much steam or electrical energy it takes to heat oil to a desired temperature. Light oils have a low specific heat, whereas heavier oils have a higher specific heat.

Calorific Value

The calorific value is the measurement of heat or energy produced, and is measured either as gross calorific value or net calorific value. The difference being the latent heat of condensation of the water vapour produced during the combustion process. Gross calorific value (GCV) assumes all vapour produced during the combustion process is fully condensed. Net calorific value (NCV) assumes the water leaves with the combustion products without fully being condensed. Fuels should be compared based on the net calorific value.

The calorific value of coal varies considerably depending on the ash, moisture content and the type of coal while calorific value of fuel oils are much more consistent. The typical Gross Calorific Values of some of the commonly used liquid fuels are given below:

Fuel Oil	Gross Calorific Value (kCal/kg)
Kerosene	- 11,100
Diesel Oil	- 10,800
L.D.O	- 10,700
Furnace Oil	- 10,500
LSHS	- 10,600

Sulphur

The amount of sulphur in the fuel oil depends mainly on the source of the crude oil and to a lesser extent on the refining process. The normal sulfur content for the residual fuel oil (furnace oil) is in the order of 2-4 %.

Typical figures are:

Fuel oil	Percentage of Sulphur
Kerosene	0.05 – 0.2
Diesel Oil	0.05 – 0.25
L.D.O	0.5 – 1.8
Furnace Oil	2.0 – 4.0
LSHS	< 0.5

The main disadvantage of sulphur is the risk of corrosion by sulphuric acid formed during and after combustion, and condensing in cool parts of the chimney or stack, air pre heater and economiser.

Ash Content

The ash value is related to the inorganic material in the fuel oil. The ash levels of distillate fuels are negligible. Residual fuels have more of the ash-forming constituents. These salts may be compounds of sodium, vanadium, calcium, magnesium, silicon, iron, aluminum, nickel, etc.

Typically, the ash value is in the range 0.03–0.07%. Excessive ash in liquid fuels can cause fouling deposits in the combustion equipment. Ash has erosive effect on the burner tips, causes damage to the refractories at high temperatures and gives rise to high temperature corrosion and fouling of equipments.

Carbon Residue

Carbon residue indicates the tendency of oil to deposit a carbonaceous solid residue on a hot surface, such as a burner or injection nozzle, when its vaporisable constituents evaporate. Residual oil contain carbon residue ranging from 1 percent or more.

Water Content

Water content of furnace oil when supplied is normally very low as the product at refinery site is handled hot and maximum limit of 1% is specified in the standard.

Water may be present in free or emulsified form and can cause damage to the inside furnace surfaces during combustion especially if it contains dissolved salts. It can also cause spluttering of the flame at the burner tip, possibly extinguishing the flame and reducing the flame temperature or lengthening the flame.

Typical specification of fuel oil is summarised in the Table 1.2.

TABLE 1.2 TYPICAL SPECIFICATION OF FUEL OILS

Properties	Fuel Oils		
	Furnace Oil	**LS.H.S.**	**L.D.O.**
Density (Approx. g/cc at 15°C)	0.89–0.95	0.88–0.98	0.85–0.87
Flash Point (°C)	66	93	66
Pour Point (°C)	20	72	18
G.C.V. (kCal/kg)	10,500	10,600	10,700
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Upto 4.0	Upto 0.5	Upto 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25
Ash % Wt. Max.	0.1	0.1	0.02

Storage of Fuel oil

It can be potentially hazardous to store furnace oil in barrels. A better practice is to store it in cylindrical tanks, either above or below the ground. Furnace oil, that is delivered, may contain dust, water and other contaminants.

The sizing of storage tank facility is very important. A recommended storage estimate is to provide for at least 10 days of normal consumption. Industrial heating fuel storage tanks are generally vertical mild steel tanks mounted above ground. It is prudent for safety and environmental reasons to build bund walls around tanks to contain accidental spillages.

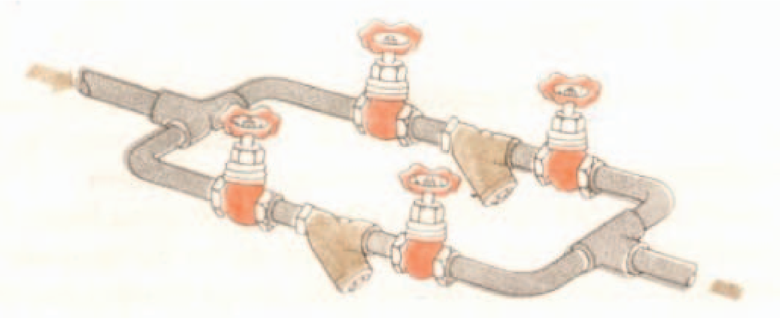
As a certain amount of settlement of solids and sludge will occur in tanks over time, cleaning should be carried out at regular intervals-annually for heavy fuels and every two years for light fuels. A little care should be taken when oil is decanted from the tanker to storage tank. All leaks from joints, flanges and pipelines must be attended at the earliest. Fuel oil should be free from possible contaminants such as dirt, sludge and water before it is fed to the combustion system.

LOSS OF EVEN ONE DROP OF OIL EVERY SECOND CAN COST YOU OVER 4000 LITRES A YEAR

Removal of Contaminants

Furnace oil arrives at the factory site either in tank lorries by road or by rail. Oil is then decanted into the main storage tank. To prevent contaminants such as rags, cotton waste, loose nuts or bolts or screws entering the system and damaging the pump, coarse strainer of 10 mesh size (not more than 3 holes per linear inch) is positioned on the entry pipe to the storage tanks.

Progressively finer strainers should be provided at various points in the oil supply system to filter away finer contaminants such as external dust and dirt, sludge or free carbon. It is advisable to provide these filters in duplicate to enable one filter to be cleaned while oil supply is maintained through the other.



The Figure 1.1 gives an illustration of the duplex system of arrangement of strainers.

Figure. 1.1 Duplex Arrangement of Strainers in a Pipeline

The Table 1.3 gives sizing of strainers at various locations.

TABLE 1.3 SIZING OF STRAINERS

Location	Strainer Sizes	
	Mesh	Holes/Linear inch
Between rail/tank lorry decanting point and main storage tank	10	3
Between service tank and pre-heater	40	6
Between pre-heater and burner	100	10

Pumping

Heavy fuel oils are best pumped using positive displacement pumps, as they are able to get fuel moving when it is cold. A circulation gear pump running on LDO should give between 7000-10000 hours of service. Diaphragm pumps have a shorter service life, but are easier and less expensive to repair. A centrifugal pump is not recommended, because as the oil viscosity increases, the efficiency of the pump drops sharply and the horsepower required increases. Light fuels are best pumped with centrifugal or turbine pumps. When higher pressures are required, piston or diaphragm pumps should be used.

Storage Temperature and Pumping Temperature

The viscosity of furnace oil and LSHS increases with decrease in temperature, which makes it difficult to pump the oil. At low ambient temperatures (below 25°C), furnace oil is not easily pumpable. To circumvent this, preheating of oil is accomplished in two ways: (a) the entire tank may be preheated. In this form of bulk heating, steam coils are placed at the bottom of the tank, which is fully insulated; (b) the oil can be heated as it flows out with an outflow heater. To reduce steam requirements, it is advisable to insulate tanks where bulk heating is used.

Bulk heating may be necessary if flow rates are high enough to make outflow heaters of adequate capacity impractical, or when a fuel such as Low Sulphur Heavy Stock (LSHS) is used. In the case of outflow heating, only the oil, which leaves the tank, is heated to the pumping temperature. The outflow heater is essentially a heat exchanger with steam or electricity as the heating medium.

Temperature Control

Thermostatic temperature control of the oil is necessary to prevent overheating, especially when oil flow is reduced or stopped. This is particularly important for electric heaters, since oil may get carbonized when there is no flow and the heater is on. Thermostats should be provided at a region where the oil flows freely into the suction pipe. The temperature at which oil can readily be pumped depends on the grade of oil being handled. Oil should never be stored at a temperature above that necessary for pumping as this leads to higher energy consumption.

1.3 Properties of Coal

Coal Classification

Coal is classified into three major types namely anthracite, bituminous, and lignite. However there is no clear demarcation between them and coal is also further classified as semi-anthracite, semi-bituminous, and sub-bituminous. Anthracite is the oldest coal from geological perspective. It is a hard coal composed mainly of carbon with little volatile content and practically no moisture. Lignite is the youngest coal from geological perspective. It is a soft coal composed mainly of volatile matter and moisture content with low fixed carbon. Fixed carbon refers to carbon in its free state, not combined with other elements. Volatile matter refers to those combustible constituents of coal that vaporize when coal is heated.

The common coals used in Indian industry are bituminous and sub-bituminous coal. The gradation of Indian coal based on its calorific value is as follows:

Grade	Calorific Value Range (in kCal/Kg)
A	Exceeding 6200
B	5600 – 6200
C	4940 – 5600
D	4200 – 4940
E	3360 – 4200
F	2400 – 3360
G	1300 – 2400

Normally D, E and F coal grades are available to Indian Industry.

The chemical composition of coal has a strong influence on its combustibility. The properties of coal are broadly classified as

1. Physical properties
2. Chemical properties

Physical Properties

Heating Value:

The heating value of coal varies from coal field to coal field. The typical GCVs for various coals are given in the Table 1.4.

TABLE 1.4 GCV FOR VARIOUS COALS

Parameter	Lignite (Dry Basis)	Indian Coal	Indonesian Coal	South African Coal
GCV (kCal/kg)	4,500*	4,000	5,500	6,000

*GCV of lignite on '*as received basis*' is 2500 – 3000

Analysis of Coal

There are two methods: ultimate analysis and proximate analysis. The ultimate analysis determines all coal component elements, solid or gaseous and the proximate analysis determines only the fixed carbon, volatile matter, moisture and ash percentages. The ultimate analysis is determined in a properly equipped laboratory by a skilled chemist, while proximate analysis can be determined with a simple apparatus. It may be noted that proximate has no connection with the word "approximate".

Measurement of Moisture

Determination of moisture is carried out by placing a sample of powdered raw coal of size 200-micron size in an uncovered crucible and it is placed in the oven kept at 108±2°C along with the lid. Then the sample is cooled to room temperature and weighed again. The loss in weight represents moisture.

Measurement of Volatile Matter

Fresh sample of crushed coal is weighed, placed in a covered crucible, and heated in a furnace at 900 ± 15°C. For the methodologies including that for carbon and ash, refer to IS 1350 part I:1984, part III, IV. The sample is cooled and weighed. Loss of weight represents moisture and volatile matter. The remainder is coke (fixed carbon and ash).

Measurement of Carbon and Ash

The cover from the crucible used in the last test is removed and the crucible is heated over the Bunsen burner until all the carbon is burned. The residue is weighed, which is the incombustible ash. The difference in weight from the previous weighing is the fixed carbon. In actual practice Fixed Carbon or FC derived by subtracting from 100 the value of moisture, volatile matter and ash.

Proximate Analysis

Proximate analysis indicates the percentage by weight of the Fixed Carbon, Volatiles, Ash, and Moisture Content in coal. The amounts of fixed carbon and volatile combustible matter directly contribute to the heating value of coal. Fixed carbon acts as a main heat generator during burning. High volatile matter content indicates easy ignition of fuel. The ash content is important in the design of the furnace grate, combustion volume, pollution control equipment and ash handling systems of a furnace. A typical proximate analysis of various coal is given in the Table 1.5.

TABLE 1.5 TYPICAL PROXIMATE ANALYSIS OF VARIOUS COALS (IN PERCENTAGE)

Parameter	Indian Coal	Indonesian Coal	South African Coal
Moisture	5.98	9.43	8.5
Ash	38.63	13.99	17
Volatile matter	20.70	29.79	23.28
Fixed Carbon	34.69	46.79	51.22

Significance of Various Parameters in Proximate Analysis

(a) Fixed carbon:

Fixed carbon is the solid fuel left in the furnace after volatile matter is distilled off. It consists mostly of carbon but also contains some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases. Fixed carbon gives a rough estimate of heating value of coal.

(b) Volatile Matter:

Volatile matters are the methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen found in coal. Thus the volatile matter is an index of the gaseous fuels present. Typical range of volatile matter is 20 to 35%.

Volatile Matter

- Proportionately increases flame length, and helps in easier ignition of coal.
- Sets minimum limit on the furnace height and volume.
- Influences secondary air requirement and distribution aspects.
- Influences secondary oil support

(c) Ash Content:

Ash is an impurity that will not burn. Typical range is 5 to 40%

Ash

- Reduces handling and burning capacity.
- Increases handling costs.
- Affects combustion efficiency and boiler efficiency
- Causes clinkering and slagging.

(d) Moisture Content:

Moisture in coal must be transported, handled and stored. Since it replaces combustible matter, it decreases the heat content per kg of coal. Typical range is 0.5 to 10%

Moisture

- Increases heat loss, due to evaporation and superheating of vapour
- Helps, to a limit, in binding fines.
- Aids radiation heat transfer.

(e) Sulphur Content:

Typical range is 0.5 to 0.8% normally.

Sulphur

- Affects clinkering and slagging tendencies
- Corrodes chimney and other equipment such as air heaters and economisers
- Limits exit flue gas temperature.

Chemical Properties

Ultimate Analysis:

The ultimate analysis indicates the various elemental chemical constituents such as Carbon, Hydrogen, Oxygen, Sulphur, etc. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases. This information is required for the calculation of flame temperature and the flue duct design etc. Typical ultimate analyses of various coals are given in the Table 1.6.

TABLE 1.6 TYPICAL ULTIMATE ANALYSIS OF COALS

Parameter	Indian Coal, %	Indonesian Coal, %
Moisture	5.98	9.43
Mineral Matter (1.1 × Ash)	38.63	13.99
Carbon	41.11	58.96
Hydrogen	2.76	4.16
Nitrogen	1.22	1.02
Sulphur	0.41	0.56
Oxygen	9.89	11.88

TABLE 1.7 RELATIONSHIP BETWEEN ULTIMATE ANALYSIS AND PROXIMATE ANALYSIS

	$\%C$	=	$0.97C + 0.7(VM - 0.1A) – M(0.6–0.01M)$
	$\%H$	=	$0.036C + 0.086\ (VM–0.1xA) - 0.0035M^2\ (1–0.02M)$
	$\%N_2$	=	$2.10 – 0.020\ VM$
where	C	=	% of fixed carbon
	A	=	% of ash
	VM	=	% of volatile matter
	M	=	% of moisture

Note: The above equation is valid for coal containing greater than 15% Moisture content.

Storage, Handling and Preparation of Coal

Uncertainty in the availability and transportation of fuel necessitates storage and subsequent handling. Stocking of coal has its own disadvantages like build-up of inventory, space constraints, deterioration in quality and potential fire hazards. Other minor losses associated with the storage of coal include oxidation, wind and carpet loss. A 1% oxidation of coal has the same effect as 1% ash in coal, wind losses may account for nearly 0.5 – 1.0% of the total loss.

The main goal of good coal storage is to minimise carpet loss and the loss due to spontaneous combustion. Formation of a soft carpet, comprising of coal, dust, and soil causes carpet loss. On the other hand, gradual temperature builds up in a coal heap, on account of oxidation may lead to spontaneous combustion of coal in storage.

The measures that would help in reducing the carpet losses are as follows:

1. Preparing a hard ground for coal to be stacked upon.
2. Preparing standard storage bays out of concrete and brick.

In process Industry, modes of coal handling range from manual to conveyor systems. It would be advisable to minimise the handling of coal so that further generation of fines and segregation effects are reduced.

Preparation of Coal

Preparation of coal prior to feeding into the boiler is an important step for achieving good combustion. Large and irregular lumps of coal may cause the following problems:

1. Poor combustion conditions and inadequate furnace temperature.
2. Higher excess air resulting in higher stack loss.
3. Increase of unburnts in the ash.
4. Low thermal efficiency.

(a) Sizing of Coal

Proper coal sizing is one of the key measures to ensure efficient combustion. Proper coal sizing, with specific relevance to the type of firing system, helps towards even burning, reduced ash losses and better combustion efficiency.

Coal is reduced in size by crushing and pulverizing. Pre-crushed coal can be economical for smaller units, especially those which are stoker fired. In a coal handling system, crushing is limited to a top size of 6 or 4 mm. The devices most commonly used for crushing are the rotary breaker, the roll crusher and the hammer mill.

It is necessary to screen the coal before crushing, so that only oversized coal is fed to the crusher. This helps to reduce power consumption in the crusher. Recommended practices in coal crushing are:

1. Incorporation of a screen to separate fines and small particles to avoid extra fine generation in crushing.
2. Incorporation of a magnetic separator to separate iron pieces in coal, which may damage the crusher.

The Table 1.8 gives the proper size of coal for various types of firing systems

TABLE 1.8 PROPER SIZE OF COAL FOR VARIOUS TYPES OF FIRING SYSTEM

S. No.	Types of Firing System	Size (in mm)
1.	Hand Firing	
	(a) Natural draft	25–75
	(b) Forced draft	25–40
2.	Stoker Firing	
	(a) Chain grate	
	i) Natural draft	25–40
	ii) Forced draft	15–25
	(b) Spreader Stoker	15–25
3.	Pulverized Fuel Fired	75% below 75 micron*
4.	Fluidized bed boiler	< 10 mm

*1 Micron = 1/1000 mm

(b) Conditioning of Coal

The fines in coal present problems in combustion on account of segregation effects. Segregation of fines from larger coal pieces can be reduced to a great extent by conditioning coal with water. Water helps fine particles to stick to the bigger lumps due to surface tension of the moisture, thus stopping fines from falling through grate bars or being carried away by the furnace draft. While tempering the coal, care should be taken to ensure that moisture addition is uniform and preferably done in a moving or falling stream of coal.

If the percentage of fines in the coal is very high, wetting of coal can decrease the percentage of unburnt carbon and the excess air level required to be supplied for combustion. Table 1.9 shows the extent of wetting, depending on the percentage of fines in coal.

TABLE 1.9 EXTENT OF WETTING: FINES VS SURFACE MOISTURE IN COAL

Fines (%)	Surface Moisture (%)
10 – 15	4 – 5
15 – 20	5 – 6
20 – 25	6 – 7
25 – 30	7 – 8

(c) Blending of Coal

In case of coal lots having excessive fines, it is advisable to blend the predominantly lumped coal with lots containing excessive fines. Coal blending may thus help to limit the extent of fines in coal being fired to not more than 25%. Blending of different qualities of coal may also help to supply a uniform coal feed to the boiler.

The proximate and ultimate analysis of various coals are given in Table 1.10 and 1.11.

TABLE 1.10 PROXIMATE ANALYSIS OF TYPICAL COAL

	Lignite	Bituminous coal (Sample I)	Bituminous Coal (Sample II)	Indonesian Coal
Moisture (%)	50	5.98	4.39	9.43
Ash (%)	10.41*	38.65	47.86	13.99
Volatile matter (%)	47.76*	20.70	17.97	29.79
Fixed carbon (%)	41.83*	34.69	29.78	46.79

*Dry Basis

TABLE 1.11 ULTIMATE ANALYSIS OF VARIOUS COALS

	Bituminous Coal (Sample I)	Bituminous Coal (Sample II)	Indonesian Coal
Moisture (%)	5.98	4.39	9.43
Mineral matter (%)	38.63	47.86	13.99
Carbon (%)	42.11	36.22	58.96
Hydrogen (%)	2.76	2.64	4.16
Nitrogen (%)	1.22	1.09	1.02
Sulphur (%)	0.41	0.55	0.56
Oxygen (%)	9.89	7.25	11.88
GCV (kCal/kg)	4000	3500	5500

1.4 Properties of Gaseous Fuels

Gaseous fuels in common use are liquefied petroleum gases (LPG), Natural gas, producer gas, blast furnace gas, coke oven gas etc. The calorific value of gaseous fuel is expressed in Kilocalories per normal cubic meter (kCal/Nm^3) i.e. at normal temperature (20°C) and pressure (760 mm Hg).

Calorific Value

Since most gas combustion appliances cannot utlilize the heat content of the water vapour, gross calorific value is of little interest. Fuel should be compared based on the net calorific value. This is especially true for natural gas, since increased hydrogen content results in high water formation during combustion.

Typical physical and chemical properties of various gaseous fuels are given in Table 1.12.

TABLE 1.12 TYPICAL PHYSICAL AND CHEMICAL PROPERTIES OF VARIOUS GASEOUS FUELS.

Fuel Gas	Relative Density	Higher Heating Value kCal/Nm^3	Air/Fuel ratio-m^3 of air to m^3 of Fuel	Flame Temp. °C	Flame Speed m/s
Natural Gas	0.6	9350	10	1954	0.290
Propane	1.52	22200	25	1967	0.460
Butane	1.96	28500	32	1973	0.870

LPG

LPG is a predominant mixture of propane and Butane with a small percentage of unsaturates (Propylene and Butylene) and some lighter C_2 as well as heavier C_5 fractions. Included in the LPG range are propane (C_3H_8), Propylene(C_3H_6), normal and iso-butane (C_4H_{10}) and Butylene(C_4H_8).

LPG may be defined as those hydrocarbons, which are gaseous at normal atmospheric pressure, but may be condensed to the liquid state at normal temperature, by the application of moderate pressures. Although they are normally used as gases, they are stored and transported as liquids under pressure for convenience and ease of handling. Liquid LPG evaporates to produce about 250 times volume of gas.

LPG vapour is denser than air: butane is about twice as heavy as air and propane about one and a half times as heavy as air. Consequently, the vapour may flow along the ground and into drains sinking to the lowest level of the surroundings and be ignited at a considerable distance from the source of leakage. In still air vapour will disperse slowly. Escape of even small quantities of the liquefied gas can give rise to large volumes of vapour / air mixture and thus cause considerable hazard. To aid in the detection of atmospheric leaks, all LPG's are required to be odorized. There should be adequate ground level ventilation where LPG is stored. For this very reason LPG cylinders should not be stored in cellars or basements, which have no ventilation at ground level.

Natural Gas

Methane is the main constituent of Natural gas and accounting for about 95% of the total volume. Other components are: Ethane, Propane, Butane, Pentane, Nitrogen, Carbon Dioxide, and traces of other gases. Very small amounts of sulphur compounds are also present. Since methane is the largest component of natural gas, generally properties of methane are used when comparing the properties of natural gas to other fuels.

Natural gas is a high calorific value fuel requiring no storage facilities. It mixes with air readily and does not produce smoke or soot. It has no sulphur content. It is lighter than air and disperses into air easily in case of leak. A typical comparison of carbon contents in oil, coal and gas is given in the table 1.13.

TABLE 1.13 COMPARISON OF CHEMICAL COMPOSITION OF VARIOUS FUELS

	Fuel Oil	Coal	Natural Gas
Carbon	84	41.11	74
Hydrogen	12	2.76	25
Sulphur	3	0.41	-
Oxygen	1	9.89	Trace
Nitrogen	Trace	1.22	0.75
Ash	Trace	38.63	-
Water	Trace	5.98	-

1.5 Properties of Agro Residues

The use of locally available agro residues is on the rise. This includes rice husk, coconut shells, groundnut shells, Coffee husk, Wheat stalk etc. The properties of a few of them are given in the table 1.14 and 1.15.

TABLE 1.14 PROXIMATE ANALYSIS OF TYPICAL AGRO RESIDUES

	Deoiled Bran	Paddy Husk	Saw Dust	Coconut Shell
Moisture	7.11	10.79	37.98	13.95
Ash	18.46	16.73	1.63	3.52
Volatile Matter	59.81	56.46	81.22	61.91
Fixed Carbon	14.62	16.02	17.15	20.62

TABLE 1.15 ULTIMATE ANALYSIS OF TYPICAL AGRO RESIDUES

	Deoiled Bran	Paddy Husk	Saw Dust	Coconut Shell
Moisture	7.11	10.79	37.98	13.95
Mineral Matter	19.77	16.73	1.63	3.52
Carbon	36.59	33.95	48.55	44.95
Hydrogen	4.15	5.01	6.99	4.99
Nitrogen	0.82	0.91	0.80	0.56
Sulphur	0.54	0.09	0.10	0.08
Oxygen	31.02	32.52	41.93	31.94
GCV (kCal/kg)	3151	3568	4801	4565

1.6 Combustion

Principle of Combustion

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat, or heat and light. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen.

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 kCals, 28922 kCals & 2224 kCals 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 kCals/kg of carbon) Carbon burned to CO_2 will produce more heat per pound of fuel than when CO or smoke are produced.

$$\begin{array}{llcll}
C & + O_2 & \rightarrow & CO_2 & + \text{ 8084 kCals/kg of Carbon} \\
2C & + O_2 & \rightarrow & 2\,CO & + \text{ 2430 kCals/kg of Carbon} \\
2H_2 & + O_2 & \rightarrow & 2H_2O & + \text{ 28,922 kCals/kg of Hydrogen} \\
S & + O_2 & \rightarrow & SO_2 & + \text{ 2,224 kCals/kg of Sulphur}
\end{array}$$

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

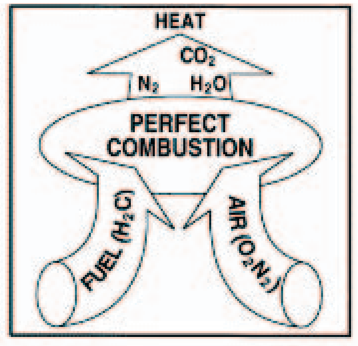
3 T's of Combustion

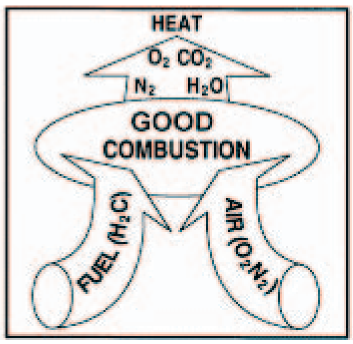
The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the "three T's" of combustion which are (1) Temperature high enough to ignite and maintain ignition of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time sufficient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

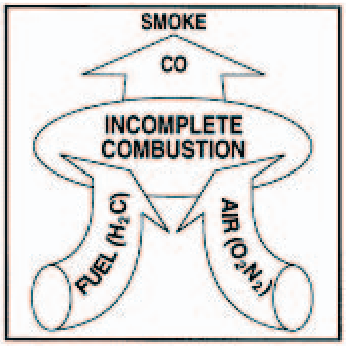
Commonly used fuels like natural gas and propane generally consist of carbon and hydrogen. Water vapor is a by-product of burning hydrogen. This robs heat from the flue gases, which would otherwise be available for more heat transfer.

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°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_2O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air,.

Rules for combustion of oil

1. Atomize the oil completely to produce a fine uniform spray
2. Mix the air and fuel thoroughly
3. Introduce enough air for combustion, but limit the excess air to a maximum of 15%
4. Keep the burners in good condition

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	2
S	32
N_2	28
CO_2	44
SO_2	64
H_2O	18

$C + O_2 \rightarrow CO_2$

$H_2 + 1/2O_2 \rightarrow H_2O$

$S + O_2 \rightarrow SO_2$

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

$(85.9)\ C + (85.9 \times 2.67)\ O2 \rightarrow 315.25\ CO_2$

$2H_2 + O_2 \rightarrow 2H_2O$

$4 + 32 \rightarrow 36$

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

$(12)\ H_2 + (12 \times 8)\ O2 \rightarrow (12 \text{ x } 9)\ H_2O$

$S + O_2 \rightarrow SO_2$

$32 + 32 \rightarrow 64$

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

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

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

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

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

$$= 15.5\ \%$$

Calculation of constituents of flue gas with excess air

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

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

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

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 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

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

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

$$= \frac{7.16}{72.956} \times 100 \ = 10\%$$

Theoretical O_2% by volume $= \dfrac{5.58\,x100}{72.956} \times 100 = 7.5\%$

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.

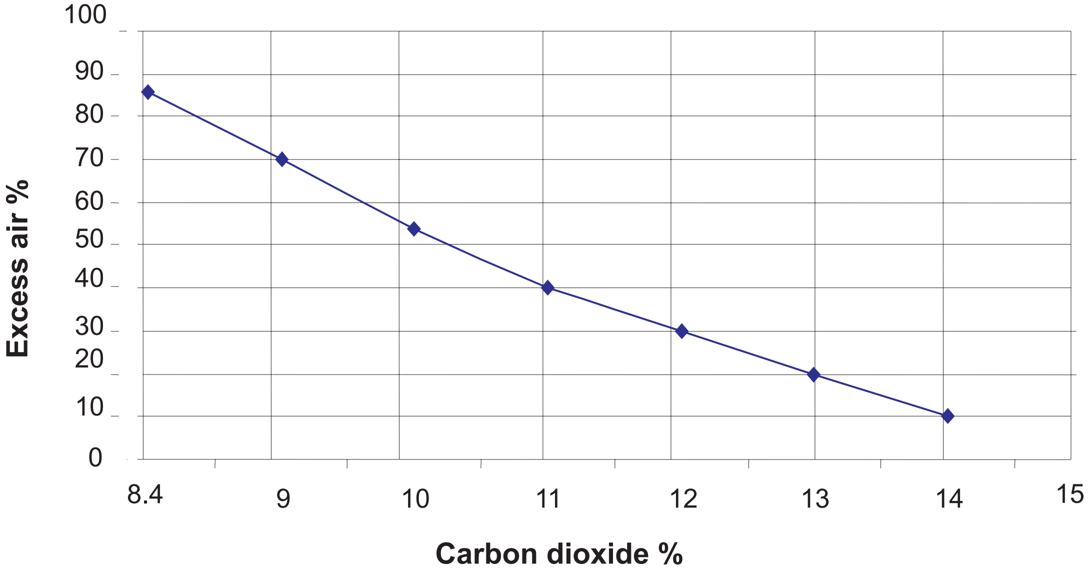


Figure 1.2 Relation Between CO_2 and Excess Air for Fuel Oil

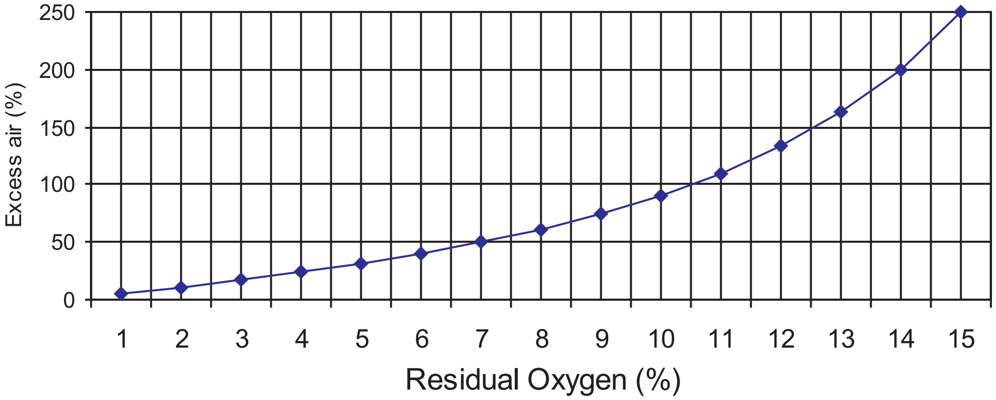


Figure 1.3: Relation Between Residual Oxygen and Excess Air

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.

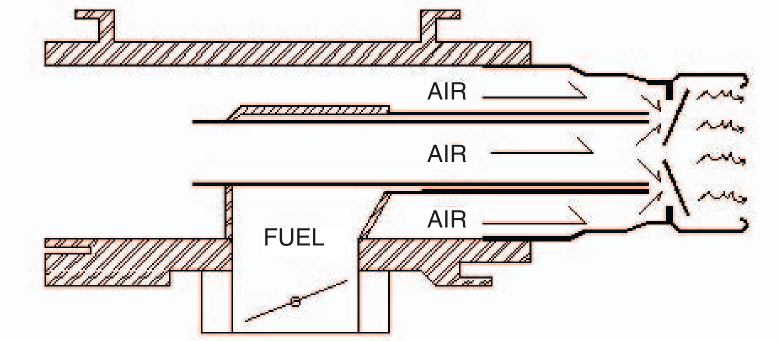


Figure 1.4 Burner Head

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 kCals and minimum rate is 50,000 kCals, 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 stoichiometric air.

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 stoichiometric quantity of air. Complete combustion is not achieved unless an excess of air is supplied.

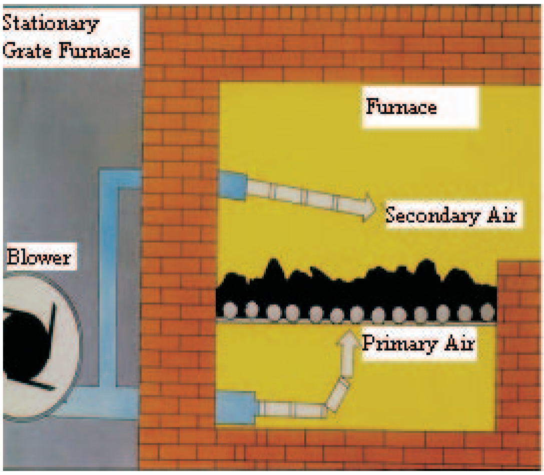


Figure 1.5 Coal Combustion

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 require 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°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.

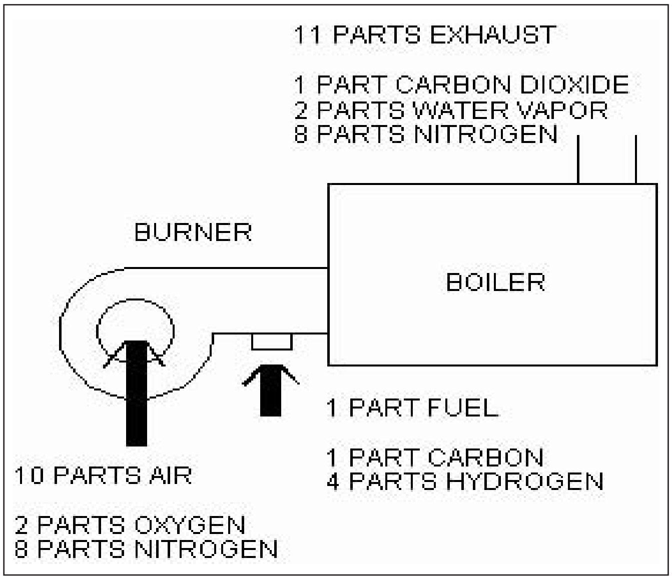


Figure 1.6 Combustion of Natural Gas

Low-And High-Pressure Gas Burners.

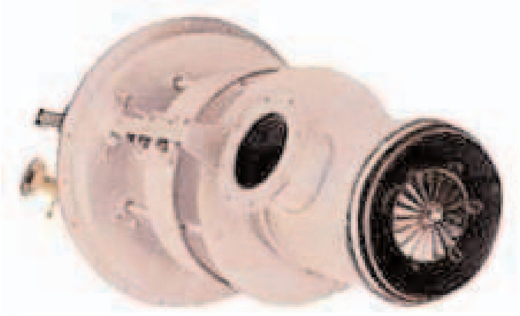


Figure 1.7 Low Pressure Gas Burner

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.

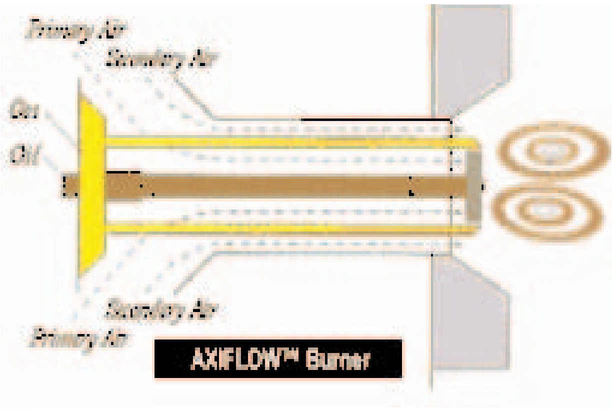


Figure 1.8 High Pressure Gas Mixer

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 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 is in the order of 5%.

1.10 Draft System

The function of draft in a combustion system is to exhaust the products of combustion into the atmosphere. The draft 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 draft artificially produced by fans. Three basic types of drafts that are applied 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.

1.11 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	
1)	Name two liquid fuels, solid fuels and gaseous fuels used in boilers.
2)	Which parameter influences the Viscosity of liquid fuel?
3)	Which element in fuel oil influences corrosion?
4)	What is the significance of pre-heating furnace oil before burning?
5)	What are the effects of contaminants in liquid fuels?
6)	Explain the difference between gross calorific value and net calorific value.
7)	What is the difference between proximate analysis and ultimate analysis of coal?
8)	What are the uses of proximate and ultimate analysis?
9)	Explain why natural gas requires least amount of excess air?
10)	What is the effect of fines on coal combustion and how to overcome them?
11)	What are the major constituent of LPG and Natural gas?
12)	Why excess air is required for complete combustion?
13)	What is the typical stoichiometric air fuel ratio for furnace oil?
14)	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?

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