Unit 2:
Energy Efficiency in Thermal Utilities
Introduction to Fuels:
The selection of right type of fuel (solid/liquid/gaseous) depends on various factors such as availability, storage, handling, pollution and landed cost of fuel.

Properties of Liquid Fuels:

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.

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.
Instrument: hydrometer.

<table>
<thead>
<tr>
<th>Fuel Oil</th>
<th>L.D.O</th>
<th>Furnace oil</th>
<th>L.S.H.S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light Diesel Oil</td>
<td></td>
<td>Low Sulphur Heavy Stock</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.85-0.87</td>
<td>0.89-0.95</td>
<td>0.88-0.98</td>
</tr>
</tbody>
</table>
**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. Unit: Stokes / Centistokes. **Instrument : Viscometer.**

**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 deg. 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 10C. The unit of specific heat is kcal / kg 0 C.
Calorific Value:
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.

<table>
<thead>
<tr>
<th>Fuel Oil</th>
<th>Gross Calorific Value (kCal/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>11,100</td>
</tr>
<tr>
<td>Diesel Oil</td>
<td>10,800</td>
</tr>
<tr>
<td>L.D.O</td>
<td>10,700</td>
</tr>
<tr>
<td>Furnace Oil</td>
<td>10,500</td>
</tr>
<tr>
<td>LSHS</td>
<td>10,600</td>
</tr>
</tbody>
</table>

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 sulphur content for the residual fuel oil (furnace oil) is in the order of 2-4 %.
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.

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 contains carbon residue ranging from 1 percent or more.

Typical figures are:

<table>
<thead>
<tr>
<th>Fuel oil</th>
<th>Percentage of Sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>0.05—0.2</td>
</tr>
<tr>
<td>Diesel Oil</td>
<td>0.05—0.25</td>
</tr>
<tr>
<td>L.D.O</td>
<td>0.5—1.8</td>
</tr>
<tr>
<td>Furnace Oil</td>
<td>2.0—4.0</td>
</tr>
<tr>
<td>LSHS</td>
<td>&lt; 0.5</td>
</tr>
</tbody>
</table>
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. Refer Table 1.2

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

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
<table>
<thead>
<tr>
<th>Location</th>
<th>Strainer Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mesh</td>
</tr>
<tr>
<td>Between rail/tank lorry decanting point and main storage tank</td>
<td>10</td>
</tr>
<tr>
<td>Between service tank and pre-heater</td>
<td>40</td>
</tr>
<tr>
<td>Between pre-heater and burner</td>
<td>100</td>
</tr>
</tbody>
</table>
The positive displacement pump provides an approximate constant flow at fixed speed, despite changes in the counter pressure. Two main types of positive displacement pumps exist:

**Rotary pumps**

**Reciprocating pumps**

This is further broken up into sub-groups:

**Rotary**
- Helical rotor or progressive cavity pumps
- Peristaltic or hose pumps
- Rotary Lobe or gear pumps

**Reciprocating**
- Diaphragm pumps
- Piston pumps
- Bucket pumps (windmills)
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.

THERMOSTAT -- An automatic control device designed to be responsive to temperature and typically used to maintain set temperatures
**Typical applications**
- Lubricating oil temperature control
- Jacket water high temperature (HT)
- Secondary water low temperature (LT)
- Heat recovery
- Water saving applications
- Boiler inlet temperature control
- Co-generation, cooling towers
- Temperature mixing or diverting
- Engine and compressor cooling system

**Key benefits**
- No external power source required - simple, low cost installation
- No user setting needed - 'fit and forget' solution
- Small number of parts - simple maintenance and low cost of ownership
- Robust design capable of high vibration and shock applications
- Easy installation, operates in any mounting position
- Automatic self-sensing control with positive proportional valve action

**Key features**
- Flow rates of 56 - 280 m³/hr
  (245 - 1232 US gpm)
- Combinations available:
  Housings in steel, stainless steel
- DN100 - DN150 (4 - 6") pipe size
- Flanged connections
- Tamper-proof temperature settings from 13°C to 116°C (55°F to 240°F)
- Pressure ratings:
  - 45 bar (655 psi) 4" only
  - 16 bar (230 psi)
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. Grades D, E and f are available to Indian Industry.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Calorific Value Range (in kCal/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Exceeding 6200</td>
</tr>
<tr>
<td>B</td>
<td>5600 – 6200</td>
</tr>
<tr>
<td>C</td>
<td>4940 – 5600</td>
</tr>
<tr>
<td>D</td>
<td>4200 – 4940</td>
</tr>
<tr>
<td>E</td>
<td>3360 – 4200</td>
</tr>
<tr>
<td>F</td>
<td>2400 – 3360</td>
</tr>
<tr>
<td>G</td>
<td>1300 – 2400</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lignite (Dry Basis)</th>
<th>Indian Coal</th>
<th>Indonesian Coal</th>
<th>South African Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCV (kcal/kg)</td>
<td>4,500 *</td>
<td>4,000</td>
<td>5,500</td>
<td>6,000</td>
</tr>
</tbody>
</table>

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.
Fuel Analysis Laboratory

Analysis of moisture, volatile matter, ash content and fixed carbon of solid and liquid fuel samples.
Coal analyses may be presented in the form of “proximate” and “ultimate” analyses, whose analytical conditions are prescribed by organizations such as the ASTM. A typical proximate analysis includes the moisture, ash, volatile matter, and fixed carbon contents. (Fixed carbon is the material, other than ash, that does not vaporize when heated in the absence of air).
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.
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

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:

**Table 1.6: Typical Ultimate Analyses of Coals**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Indian Coal, %</th>
<th>Indonesian Coal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>5.98</td>
<td>9.43</td>
</tr>
<tr>
<td>Mineral Matter (1.1 x Ash)</td>
<td>38.63</td>
<td>13.99</td>
</tr>
<tr>
<td>Carbon</td>
<td>41.11</td>
<td>58.96</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.76</td>
<td>4.16</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.22</td>
<td>1.02</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.41</td>
<td>0.56</td>
</tr>
<tr>
<td>Oxygen</td>
<td>9.89</td>
<td>11.88</td>
</tr>
<tr>
<td>%C</td>
<td>[0.97C + 0.7(VM - 0.1A) - M(0.6-0.01M)]</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>%H</td>
<td>[0.036C + 0.086(VM - 0.1xA) - 0.0035M^2 (1-0.02M)]</td>
<td></td>
</tr>
<tr>
<td>%N₂</td>
<td>2.10 - 0.020 VM</td>
<td></td>
</tr>
</tbody>
</table>

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 loses 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 unburntts in the ash.
4. Low thermal efficiency.
The Table 1.8 gives the proper size of coal for various types of firing systems.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Types of Firing System</th>
<th>Size (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Hand Firing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Natural draft</td>
<td>25-75</td>
</tr>
<tr>
<td></td>
<td>(b) Forced draft</td>
<td>25-40</td>
</tr>
<tr>
<td>2.</td>
<td>Stoker Firing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Chain grate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>i) Natural draft</td>
<td>25-40</td>
</tr>
<tr>
<td></td>
<td>ii) Forced draft</td>
<td>15-25</td>
</tr>
<tr>
<td></td>
<td>(b) Spreader Stoker</td>
<td>15-25</td>
</tr>
<tr>
<td>3.</td>
<td>Pulverized Fuel Fired</td>
<td>75% below 75 micron*</td>
</tr>
<tr>
<td>4</td>
<td>Fluidized bed boiler</td>
<td>&lt; 10 mm</td>
</tr>
</tbody>
</table>

*1 Micron = 1/1000 mm
(b) Conditioning of Coal

<table>
<thead>
<tr>
<th>Table 1.9 Extent of Wetting: Fines Vs Surface Moisture in Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fines (%)</strong></td>
</tr>
<tr>
<td>10 - 15</td>
</tr>
<tr>
<td>15 - 20</td>
</tr>
<tr>
<td>20 - 25</td>
</tr>
<tr>
<td>25 - 30</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th></th>
<th>Lignite</th>
<th>Bituminous coal (Sample I)</th>
<th>Bituminous Coal (Sample II)</th>
<th>Indonesian Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>50</td>
<td>5.98</td>
<td>4.39</td>
<td>9.43</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>10.41*</td>
<td>38.65</td>
<td>47.86</td>
<td>13.99</td>
</tr>
<tr>
<td>Volatile matter (%)</td>
<td>47.76*</td>
<td>20.70</td>
<td>17.97</td>
<td>29.79</td>
</tr>
<tr>
<td>Fixed carbon (%)</td>
<td>41.83*</td>
<td>34.69</td>
<td>29.78</td>
<td>46.79</td>
</tr>
</tbody>
</table>

*Dry Basis
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/Nm3) i.e. at normal temperature (20 deg.C) and pressure (760 mm Hg).

Calorific Value - Since most gas combustion appliances cannot utilize 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.
LPG
LPG is a predominant mixture of propane and Butane with a small percentage of unsaturates (Propylene and Butylene) and some lighter C2 as well as heavier C5 fractions.

There should be adequate ground level ventilation where LPG is stored.

Natural Gas
Methane is the main constituent of Natural gas and accounting for about 95% of the total volume.
### Table 1.13  Comparison of Chemical Composition of Various Fuels

<table>
<thead>
<tr>
<th></th>
<th>Fuel Oil</th>
<th>Coal</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon</strong></td>
<td>84</td>
<td>41.11</td>
<td>74</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td>12</td>
<td>2.76</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sulphur</strong></td>
<td>3</td>
<td>0.41</td>
<td>-</td>
</tr>
<tr>
<td><strong>Oxygen</strong></td>
<td>1</td>
<td>9.89</td>
<td>Trace</td>
</tr>
<tr>
<td><strong>Nitrogen</strong></td>
<td>Trace</td>
<td>1.22</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Ash</strong></td>
<td>Trace</td>
<td>38.63</td>
<td>-</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td>Trace</td>
<td>5.98</td>
<td>-</td>
</tr>
</tbody>
</table>
Properties of Agro Residues:

<table>
<thead>
<tr>
<th></th>
<th>Deoiled Bran</th>
<th>Paddy Husk</th>
<th>Saw Dust</th>
<th>Coconut Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>7.11</td>
<td>10.79</td>
<td>37.98</td>
<td>13.95</td>
</tr>
<tr>
<td>Ash</td>
<td>18.46</td>
<td>16.73</td>
<td>1.63</td>
<td>3.52</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>59.81</td>
<td>56.46</td>
<td>81.22</td>
<td>61.91</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>14.62</td>
<td>16.02</td>
<td>17.15</td>
<td>20.62</td>
</tr>
</tbody>
</table>

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

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.
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 (CO2), water vapor (H2O) and Sulphur Dioxide (SO2), which pass through the chimney along with the Nitrogen (N2) 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

Calculation of Stoichiometric Air

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

<table>
<thead>
<tr>
<th>Constituents</th>
<th>% By weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>85.9</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>12</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.5</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.5</td>
</tr>
<tr>
<td>$H_2O'$</td>
<td>0.35</td>
</tr>
<tr>
<td>Ash</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Element</th>
<th>Molecular Weight kg / kg mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12</td>
</tr>
<tr>
<td>O₂</td>
<td>32</td>
</tr>
<tr>
<td>H₂</td>
<td>2</td>
</tr>
<tr>
<td>S</td>
<td>32</td>
</tr>
<tr>
<td>N₂</td>
<td>28</td>
</tr>
<tr>
<td>CO₂</td>
<td>44</td>
</tr>
<tr>
<td>SO₂</td>
<td>64</td>
</tr>
<tr>
<td>H₂O</td>
<td>18</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
C & + O₂ \rightarrow CO₂ \\
H₂ & + 1/2O₂ \rightarrow H₂O \\
S & + O₂ \rightarrow SO₂
\end{align*}
\]
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 \( \frac{32}{12} \) kg i.e 2.67 kg of oxygen

\[ (85.9) C + (85.9 \times 2.67) O_2 \rightarrow 315.25 CO_2 \]

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

\[ 4 + 32 \rightarrow 36 \]

4 kg of hydrogen requires 32 kg of oxygen to form 36 kg of water, therefore 1 kg of hydrogen requires \( \frac{32}{4} \) kg i.e 8 kg of oxygen

\[ (12) H_2 + (12 \times 8) O_2 \rightarrow (12 \times 9 ) H_2O \]

\[ S + O_2 \rightarrow SO_2 \]

\[ 32 + 32 \rightarrow 64 \]

32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide, therefore 1 kg of sulphur requires \( \frac{32}{32} \) kg i.e 1 kg of oxygen
\[(0.5) \text{ S} + (0.5 \times 1) \text{ O}_2 \rightarrow 1.0 \text{ SO}_2\]

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

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. = \(\frac{324.87}{0.23}\)
(air contains 23% oxygen by wt.)
= 1412.45 kg of air

Theoretical Air required = \(\frac{1412.45}{100}\)
= 14.12 kg of air / kg of fuel

**Calculation of theoretical \(\text{CO}_2\) content in flue gases**

Nitrogen in flue gas = 1412.45 - 324.87
= 1087.58 kg

Theoretical \(\text{CO}_2\)% in dry flue gas by volume is calculated as below:

Moles of \(\text{CO}_2\) in flue gas = \(\frac{314.97}{44}\) = 7.16
Moles of \(\text{N}_2\) in flue gas = \(\frac{1087.58}{28}\) = 38.84
Moles of \(\text{SO}_2\) in flue gas = \(\frac{1}{64}\) = 0.016
Theoretical CO₂ % by volume = \( \frac{\text{Moles of CO}_2}{\text{Total moles (dry)}} \times 100 \)

\[ = \frac{7.16}{7.16 + 38.84 + 0.016} \times 100 \]

\[ = 15.5 \% \]

Calculation of constituents of flue gas with excess air

\% CO₂ measured in flue gas = 10% (measured)

\% Excess air = \( \left( \frac{\text{Theoretical } CO_2 \%}{\text{Actual } CO_2 \%} - 1 \right) \times 100 \)

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

Theoretical air required for 100 kg of fuel burnt = 1412.45 kg

Total quantity of air supply required with 55% excess air = 1412.45 \times 1.55 = 2189.30 kg

Excess air quantity = 2189.30 - 1412.45 = 776.85 kg.

\( \text{O}_2 = 776.85 \times 0.23 = 178.68 \)

\( \text{N}_2 = 776.85 - 178.68 = 598.17 \text{ kg} \)
The final constitution of flue gas with 55% excess air for every 100 kg fuel.

\[
\begin{align*}
\text{CO}_2 & = 314.97 \text{ kg} \\
\text{H}_2\text{O} & = 108.00 \text{ kg} \\
\text{SO}_2 & = 1 \text{ kg} \\
\text{O}_2 & = 178.68 \text{ kg} \\
\text{N}_2 & = 1087.58 + 598.17 \\
& = 1685.75 \text{ kg}
\end{align*}
\]

**Calculation of Theoretical CO\textsubscript{2}% in Dry Flue Gas By Volume**

Moles of CO\textsubscript{2} in flue gas \( = \frac{314.97}{44} = 7.16 \)

Moles of SO\textsubscript{2} in flue gas \( = \frac{1}{64} = 0.016 \)

Moles of O\textsubscript{2} in flue gas \( = \frac{178.68}{32} = 5.58 \)

Moles of N\textsubscript{2} in flue gas \( = \frac{1685.75}{28} = 60.20 \)

\[
\text{Theoretical CO}_2 \% \text{ by volume} = \frac{\text{Moles of CO}_2}{\text{Total moles (dry)}} \times 100
\]

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

\[
= \frac{7.16}{72.956} \times 100 = 10\%
\]

Theoretical O\textsubscript{2}% by volume \( = \frac{5.58 \times 100}{72.956} \times 100 = 7.5\% \)
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 (CO2) or oxygen (O2) 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 CO2 or O2 in flue gases should be maintained at 14 -15% in case of CO2 and 2-3% in case of O2.
Figure 1.2 Relation Between CO₂ and Excess Air for Fuel Oil
Oil Firing Burners:
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.
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.

**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.

**Complete combustion is not achieved unless an excess of air is supplied.**
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 (FBC) 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.

Fluidized bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits – compact boiler design, fuel flexibility, higher combustion efficiency and reduced emission of noxious pollutants such as SOx and NOx.

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 deg.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.
Combustion of Gas:
Combustion Characteristics of Natural Gas

Natural gas is essentially pure methane, CH4. Its combustion can be represented as follows:

\[ \text{CH}_4 + 2\text{O}_2 = \text{CO}_2 + 2\text{H}_2\text{O} \]

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.
Low-pressure burners (figure 1.7), using gas at a pressure less than 0.15 kg/cm² (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.
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%.
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.
Fig. Schematic Diagram of Thermal Power Station.
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.