**Fuel and Combustion**

* 1. **Introduction to Fuels**

Fuel is defined as any material which produces heat energy when combusted. The primary constituents of fuel are carbon and hydrogen and hence named as hydrocarbon fuel. It is denoted by the formula CnHm.

Fuels are classified into three types namely

1. Solid fuel, (b) liquid fuel and (c) gaseous fuel.

Depending upon the availability, landed cost of fuel, handling and pollution and storage, fuel can be selected for specific purpose. The knowledge of the fuel properties helps in selecting the right fuel for the right purpose and efficient use of the oil.

* 1. **Properties of fuel oil:**

To know the physico-chemical characteristics of fuel, properties should be checked. Identification of the quality of a fuel is mainly based on the following important parameters as discussed below.

(i) **Density:** It is defined as the mass per unit volume of a liquid at a standard temperature of 150C and atmospheric pressure. It is denoted by ⍴. It is expressed in kg/m3. Density of a liquid fuel is measured by an instrument called hydrometer.

Mathematically,

where

*m* is the mass of the liquid and

*V* is the volume of the liquid.

(ii) **Specific gravity:** Specific gravity or relative density is defined as the density of a liquid to the density of pure water (usually water at 40C for which density of water is 1000kg/m3). It is a dimensionless quantity. For example Specific gravity of mercury at 00C is 13.6. It is to be noted that specific gravity of substances less than 1 are lighter than water, and hence float in water.

Table 1: Specific gravity of some of the known fuel are listed below:

|  |  |  |  |
| --- | --- | --- | --- |
| **SPECIFIC GRAVITY OF VARIOUS FUEL OILS** | | | |
| **Fuel oil** | Light Diesel oil | Furnace Oil | Low Sulphur Heavy Stock (LSHS) |
| **Specific Gravity** | 0.85 - 0.87 | 0.89 - 0.95 | 0.88 -0.98 |

*Source: Bureau of Energy Efficiency*

Table 2:

|  |  |
| --- | --- |
| **SPECIFIC GRAVITY OF SOME SUBSTANCES AT 00C** | |
| **Substance** | **Specific Gravity** |
| Water | 1 |
| Seawater | 1.025 |
| Gasoline | 0.7 |
| Ethyl Alcohol | 0.79 |
| Mercury | 13.6 |
| Wood | 0.3-0.9 |
| Ice | 0.92 |
| Air (at 1 atm) | 0.0013 |
| *Source: Thermal engineering, Rathore* |  |

1. **Viscosity:** Viscosity is defined as the property of a liquid which offers resistance to the movement of one layer of liquid over another adjacent layer of liquid. Viscosity is a function of temperature. It is inversely proportional to temperature. As temperature of liquid increases, viscosity decreases. Viscosity is measured by an instrument called Redwood viscometer. Unit of viscosity is Stoke or centistokes.

Viscosity is the most important characteristic in the storage and use of fuel oil. Highly viscous fluid is very difficult to pump, hard to light the burner, and tough to operate [1]. Higher viscosity of fuel leads to poor atomization. Viscosity of fuel is related to chemical structure. Viscosity increases with increase in the chain length and decreases with increase in the number of double bonds.

1. **Flash point:** Flash point is defined as the lowest temperature at which oil will vaporize sufficiently to produce a combustible mixture of oil vapour and air above the surface of the oil. It is found by heating a quantity of the oil in a special container while passing a flame above the liquid to ignite the vapour. A distinct flash of flame occurs when the flash point temperature is reached. Oil temperature above 500C is tested by Penskey-Martens apparatus whereas oil temperature below 500C is tested by Abel apparatus [4].
2. **Fire point:** Fire point is defined as the minimum temperature at which oil vapours will continue to burn instead of just flashing.
3. **Pour Point:** It is defined as the temperature at which oil stops flowing. This happens due to increase in viscosity or from the crystallization of wax from the oil. High pour point can be seen in heavy fuel oil. For proper handing in cold areas, oil should have low pour point.
4. **Cloud Point:** It is defined as the lowest temperature at which cloudiness appears in oil when cooled in a cloud point apparatus. Cloud point is more significant than pour point in case of diesel fuel. Because flow may be stopped due to formation of wax which can clog in the fuel filter line [4]
5. **Specific heat:** Specific heat is defined as the energy required to raise the unit mass of a substance by one degree centigrade [2]. Unit of Specific heat is kJ/kg 0C or kJ/kg K. Based on the oil specific gravity, specific heat ranges from 0.22 to 0.28. Specific heat determines how much steam or electrical energy is required to raise the temperature of oil at desired value. It is to be noted that light oils have lower specific heat whereas heavier oil have higher specific heat. Specific heat of coal increases with increase in the volatile matter and decrease in C-H ratio.
6. **Calorific Value:** It is defined as the amount of heat released when a unit amount of fuel is completely burned at room temperature and the product of combustion are cooled to room temperature.

Most of the fuel contains hydrogen which forms water when burned, and the heating value of fuel will be different, depending on whether the water in the combustion products is in the liquid or vapor form. The heating value is called lower heating value or net calorific value (LHV), when the water leaves as vapour, and higher heating value or gross calorific value (HHV) when the water in the combustion gases is completely condensed and thus the heat of vapourisation is also recovered [2]. It is to be noted that fuels can be compared on the basis of 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.

Table 3 Gross Calorific Values of some of the commonly used liquid fuels are given below

|  |  |
| --- | --- |
| **Fuel Oil** | **Gross Calorific Value (kCal/kg)** |
| Kerosene | 11100 |
| Diesel Oil | 10800 |
| L.D.O | 10700 |
| Furnace Oil | 10500 |
| LSHS | 10600 |
| *Source: Bureau of Energy Efficiency* |  |

1. **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 %.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 economizer [1].

Table 4: Percentage of sulphur of some of the fuel oil is shown below

|  |  |
| --- | --- |
| **Fuel Oil** | **Percentage of Sulphur** |
| Kerosene | 0.05-0.2 |
| Diesel Oil | 0.05-0.25 |
| Light Diesel Oil | 0.5-1.8 |
| Furnace Oil | 2.0-4.0 |
| LSHS | < 0.5 |
| *Source: Bureau of Energy Efficiency* |  |

1. **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 [1].

1. 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 [1].
2. 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 [1].

Table 5: Properties of some fuel oils

|  |  |  |  |
| --- | --- | --- | --- |
| Properties | Fuel Oils | | |
| Furnace Oil | Light Diesel Oil | Low Sulphur Heavy Stock |
| Density (g/cc at 15 0C) | 0.88- 0.95 | 0.85-0.87 | 0.88-0.98 |
| Flash Point ( 0C ) | 66 | 66 | 93 |
| Pour Point (0C) | 20 | 18 | 72 |
| Gross Calorific Value (kCal/kg) | 10500 | 10700 | 10600 |
| Sulphur Total, % wt. Max | up to 4.0 | up to 1.8 | up to 0.5 |
| Water Content, % Vol, max | 1 | 0.25 | 1 |
| Ash % wt. Max | 0.1 | 0.02 | 0.1 |

*Source: Bureau of Energy Efficiency*

**Fuel oil Storage:**

Fuel oil is a general term for a number of burnable liquids made from crude oil. Engines, lamps and heaters are run on fuel oils. Fuel oil spillage can cause serious problem of water pollution and hence proper storage of fuel oil is vital. Portable container is used to store small quantity of fuel oil. In case of large quantity of fuel oil, cylindrical tanks ( horizontal or vertical) are used above or below the ground. The size of the storage tank facility should be such that it can store fuel for 10 days at normal consumption. Vertical mild steel storage tanks installed above the ground are used for storing industrial heating fuel. Fuel oil spillage to the ground can be stopped by providing bund walls around the tank.

Tank should be cleaned at regular intervals, in order to remove the solid and sludge that settles at the bottom of the tank as time proceeds. For heavy fuel, cleaning of tank should be done annually whereas for light fuel, cleaning is done in every two years. Care should be taken when oil is decanted from the tanker to the storage tank. All leaks from joints, flanges and pipelines must be attended to 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 [4]

**Solid fuel (Coal)**

Coal is a sedimentary rock composed mostly of carbon, hydrogen, oxygen, nitrogen, sulphur, moisture and ash. Among these, carbon is the main constituent. It is black or brownish-black in colour. Formation of coal takes millions of year and hence it is a non-renewable source of energy. Coal is formed by the decay of vegetable matter which is accumulated under the earth crust for millions of years and transformed by the action of heat and pressure [2]

**Classification of coal:**

Depending on the amount of carbon content and the heat energy, coal is classified into four general categories or ranks, namely anthracite, bituminous, sub-bituminous, and lignite.  These four types of coal are differentiated based on the energy output as a result of increased pressurization, heat, and time. Anthracite is the oldest coal with highest carbon content (highest rank) whereas lignite is the youngest type of coal with lowest carbon content (lowest rank). Heating value of coal mainly depend on the quantity of carbon. **Bituminous coal is** dark, hard coal having higher heating value than lignite and sub-bituminous coal, but a lower heating value than anthracite. **Sub-bituminous coal** is a dull black coal with a higher heating value than lignite.

Table 6: Types of coal with corresponding calorific value as shown below

|  |  |  |  |
| --- | --- | --- | --- |
| **Type of coal** | **Carbon (%)** | **Calorific Value (MJ/kg)** | **Uses** |
| Anthracite | 90 | 36 | Used as fuel in Steam power plant |
| Bituminous | 70 | 31.5 | Used for producting producer gas |
| Lignite | 60 | 21 | Used as fuel in power plant |

*Source: Thermal engineering, Rathore*

The common coals used in Indian industry are bituminous and sub-bituminous coal. In India, D, E and F coal grades are normally used.

Table 7: The gradation of Indian coal based on its calorific value is as follows

|  |  |
| --- | --- |
| **Grade** | **Calorific value Range (kCal/kg)** |
| A | Exceeding 6200 |
| B | 5600 -6200 |
| C | 4940-5600 |
| D | 4200-4940 |
| E | 3360-4200 |
| F | 2400-3360 |
| G | 1300-2400 |
| *Source : Bureau of Energy Efficiency* | |

The properties of coal are classified as

(a) Physical properties

(b) Chemical properties

**Physical Properties:**

**Heating value:** Heating (calorific) value of coal is very much important during the conversion of coal to other useful form of fuel. Heating value of fuel is mainly based on the geographical location.

Table 8: The gross calorific value for various coals are shown below

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Gross Calorific Value for Various Coals** | | | | |
| Parameter | Lignite (dry basis) | Indian Coal | Indonesian Coal | South African Coal |
| GCV (kCal/kg) | 4500 | 4000 | 5500 | 6000 |
| *Source: Bureau of Energy Efficiency* |  |  |  |  |

**Analysis of Coal:**

An exact mass analysis of coal is very difficult in actual practice because based on the geographical location, coal composition varies. Hence the two most important analysis are popular from the view point namely (i) Proximate analysis (ii) Ultimate analysis.

**Proximate analysis**: It indicates the percentage by mass of fixed carbon, volatile matter, moisture content and ash in coal. Heating value of coal is mainly dependent of fixed carbon and volatile matter.

**Ultimate analysis**: It gives us the accurate chemical analysis by mass of important elements of fuel 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 [2]

Table 9: Proximate analysis of various coals

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | | Percentage by mass of fuel | |
| **Fuel** | Volatile matter (%) | Moisture (%) | Fixed carbon (%) | Ash (%) |
| **Anthracite Coal** | 6 | 2 | 75 | 17 |
| **Bituminous Coal** | 21 | 6 | 35 | 38 |
| **Indonesian Coal** | 30 | 9 | 47 | 14 |

Table 10: Ultimate analysis of various coals

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Percentage by mass of dry fuel** | | | | | |
| **Fuel** | **Rank** | **C** | **H2** | **O2** | **N2** | **S** | **Mineral matter** |
| Anthracite | 101 | 88.2 | 2.7 | 1.7 | 1 | 1.2 | 5.2 |
| Medium rank coal | 401 | 81.8 | 4.9 | 4.4 | 1.8 | 1.9 | 5.2 |
| Low rank coal | 902 | 75 | 4.6 | 10.7 | 1.6 | 2.1 | 6 |
| Coke | - | 90 | 0.4 | 1.9 | - | - | 7.7 |

*Source:* *Thermal engineering, Rathore*

**Measurement of Moisture:**

A known quantity of the powdered raw coal of size 200-micron size is taken in an uncovered crucible and kept in an oven heated at 108±2°C along with the lid until constant weight is reached. The sample is then cooled to room temperature and weighed again. The difference of the oven dry weight of the coal sample and the green weight of the coal sample is used to determine the percentage of moisture content [1]

**Measurement of Volatile Matter**

**V**olatile matter is determined using IS 1350 part I:1984, part III, IV. At first fresh sample of coal is taken and crushed. It is then weighed and taken in a covered crucible, kept in a furnace and heated at 900 ± 15°C for 2 minutes. The sample is then cooled in air for 2minute to 5 minute and then cooled in a desiccators for 15minutes and weight. The difference in weight represents moisture and volatile matter. The remainder is coke (fixed carbon and ash) [1]

**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 [1]

In actual practice fixed carbon can be calculated as follows:

1. Fixed carbon ( on dry basis) = 100 – ( volatile matter + Ash)
2. Fixed carbon ( on wet basis) = 100 – ( volatile matter + Ash + moisture)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Table 11: Composition and Property Ranges of Various Ranks of Coal** | | | | |
|  | **Anthracite** | **Bituminous** | **Sub bituminous** | **Lignite** |
| Moisture (%) | 3-6 | 2-15 | 10-25 | 25-45 |
| Volatile matter (%) | 2-12 | 15-45 | 28-45 | 24-32 |
| Fixed Carbon (%) | 75-85 | 50-70 | 30-57 | 25-30 |
| Ash (%) | 4-15 | 4-15 | 3-10 | 3-15 |
| Sulphur(%) | 0.5-2.5 | 0.5-6 | 0.3-1.5 | 0.3-2.5 |
| Hydrogen (%) | 1.5-3.5 | 4.5-6 | 5.5-6.5 | 6-7.5 |
| Carbon (%) | 75-85 | 65-80 | 55-70 | 35-45 |
| Nitrogen(%) | 0.5-1 | 0.5-2.5 | 0.8-1.5 | 0.6-1.0 |
| Oxygen (%) | 5.5-9 | 4.5-10 | 15-30 | 38-48 |
| Density (g/mL) | 1.35-1.70 | 1.28-1.35 | 1.35-1.40 | 1.40-1.45 |
| *Source: Handbook of coal analysis by J.G. Speight* | | | |  |

Proximate analysis:

It indicates the percentage by mass of fixed carbon, volatile matter, ash and moisture content of coal. The amount of fixed carbon and volatile matter directly contribute to the heating value of coal.

Table 12: Proximate analysis of various coal types found worldwide is given below

|  |  |  |  |
| --- | --- | --- | --- |
| **Proximate analysis of various coals (%)** | | | |
| **Parameter** | **Indian Coal** | **Indonesian Coal** | **South African Coal** |
| Moisture | 5.98 | 9.43 | 8.5 |
| Ash | 38.63 | 13.99 | 17 |
| Volatile Matter | 20.7 | 29.79 | 23.28 |
| Fixed Carbon | 34.69 | 46.79 | 51.22 |
| *Source : Bureau of Energy Efficiency* |  |  |  |

The above parameters are having some significance on the coal properties which can be discussed as follows:

1. **Fixed Carbon:** Fixed carbon acts as a main heat generator during burning. It consists mostly of carbon but also contains some traces of hydrogen, oxygen, sulphur, and nitrogen. Fixed carbon gives the rough estimate of heating value of coal [2]
2. **Volatile matter:** Volatile matter contains methane, hydrocarbon, hydrogen, carbon monoxide and nitrogen found in coal. High volatile matter content indicates easy ignition of fuel [2]
3. **Ash:** Ash is an impurity that will not burn. It is the most important parameter during the design of furnace grate, combustion volume, pollution control equipment and ash handling system of the furnace [2]
4. **Moisture:** Heating value of coal is dependent upon moisture present in the coal. Moisture present in the coal decreases the heating value per kg of coal. The moisture content in coal ranges from 0.5 to 10%.

**Ultimate analysis of coal:**

Ultimate analysis of coal determines the chemical analysis by mass of important elements of fuel such as carbon, hydrogen, oxygen, sulphur etc. From this analysis, we can easily determine the amount of air required for combustion and the volume and composition of the combustion gases. This analysis is very much important during the calculation of flame temperature and the flue duct design.

Table 13: Ultimate analysis of coal is shown below

|  |  |  |
| --- | --- | --- |
| ULTIMATE ANALYSIS OF COALS | | |
| Parameter | Indian Coal (%) | Indonesian Coal (%) |
| Moisture | 5.98 | 9.43 |
| Mineral Matter | 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 |
| *Source : Bureau of Energy Efficiency* |  |  |

Relationship between Ultimate analysis and Proximate analysis is given by

1. Carbon (%) = 0.97C + 0.7(VM -0.1A) – M (0.6-0.01M)
2. Hydrogen (%) = 0.036C + 0.086 (VM – 0.1A) – 0.0035 M2 (1-0.02M)
3. Nitrogen (%) = 2.10 -0.020 VM

*Where,* C is the percentage of fixed carbon, A is the percentage of ash, VM is the percentage of volatile matter, and M is the percentage of moisture.

It is to be noted that the above relationship between ultimate analysis and proximate analysis is valid for coals having moisture content greater than 15%.

**Storage, handling and preparation of coal**

1. **Storage of coal:**

Industries running on coal had to store large quantities of coal as a reserve to offset during the shortage. During storage coal undergoes a series of changes by exposure to atmosphere. The process is known as weathering of coal. Weathering can be minimized by storing coal under water. Weathering can be seen with lower rank of coal.

The properties affected by the storage of coal are (i) size, (ii) friability, (iii) caking capacity, (iv) ultimate analysis, (v) calorific value, (vi0 yield of carbonization products.

Whenever coal is stored in bulk for long time, its temperature should be measured at various points of the pile from time to time. Above 700C, the risk of spontaneous inflammation is great. Therefore coal should be consumed before this critical temperature is reached. Water spraying helps only in the initial stages and not after the crossing of the danger point. As a rule, coal should not be placed near the source of heat [4]

1. **Preparation of coal:**

Preparation of coal is done by removing the undesirable materials from the Run of Mine (ROM) by employing a series of operations. Coal collected from the mine cannot be utilized directly without knowing the properties like size, ash, sulphur content, phosphorous, moisture and chlorine content. Depending upon the type of coal used by the industries, these properties are improved without putting down the physical and chemical properties of coal. Screening is the process of differentiating the size of the coal. There are various processes by which screening of coal is done namely revolving, vibrating and shaking [4]

**(c )** **Coal cleaning**:

Indian coal contains high ash. These type of coal is cleaned in order to raise the efficiency. Cleaning is done to remove the impurities such as sulfur, ash, and rock present in the coal to upgrade its value.

Initially the raw coal is unloaded, stored, conveyed, crushed. The crushed coal is then screened into coarse and fine coal fractions. Fluid such as water is used to remove the lighter coal particles from the top of the bed and the heavier impurities settled at the base which can be removed from the bottom.

Coal cleaned in the wet processes thenmust be dried in the final preparation processes.

1. **Coal washing:**

Washing of Indian coals are very difficult for the following reasons

1. large content of intimately associated mineral matter giving rise to difficult washability characteristics,
2. presence of high percentage of near gravity material at the desired density of separation,
3. wide variation in washability characteristics of coal for different horizontal and vertical sections of the same seam, and
4. low average annual production of individual mines. Thus coals that are widely used in India can be washed by using jigs, heavy medium separators (shallow bath) and cyclones [4]

**Properties of Gaseous Fuels**

The commonly used gaseous fuels are liquefied petroleum gases, 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°C) and pressure (760 mm Hg).

LPG is a mixture of propane and Butane with small traces of propylene and butylenes. On the other hand Natural Gas is a mixture of methane, ethane, propane, butane, pentane, nitrogen, CO2 and small traces of other gases. The main constituent of Natural Gas is methane (95%).

Table 14: Properties of various gaseous fuels are shown below

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Fuel Gas | Relative density | Higher Heating Value (kCal/ Nm3) | Air/Fuel ratio | Flame Temperature 0C | Flame Speed (m/s) |
| Natural Gas | 0.6 | 9350 | 10 | 1954 | 0.29 |
| Propane | 1.52 | 22200 | 25 | 1967 | 0.46 |
| Butane | 1.96 | 28500 | 32 | 1973 | 0.87 |
| *Source: Bureau of Energy Efficiency* |  |  |  |  |  |

**1.3 Combustion**

**Principle of Combustion**

Combustion is the process of burning fuel in presence of an oxidizer (Air). Heat is released by the process and thus it is called an exothermic process. Combustion can be said to be complete combustion or incomplete combustion depending upon the amount of air used in the reaction. Combustion is said to be complete when all the carbon present in the fuel is converted into carbon dioxide, all the hydrogen present is converted to water vapour, all the suphur is converted into sulphur dioxide. If combustion takes place in presence of adequate supply of oxygen, then the process is said to be incomplete combustion [2]

Basic combustion reaction:

1. **Combustion of solid and liquid fuel**

The main elements of solid and liquid fuel are C, H2, S. These elements are burnt in presence of oxidizer to produce CO, CO2, H2O, SO2. The reaction is as follows

1. *Burning of Carbon to carbon monoxide: Incomplete combustion*
2. *Burning of Carbon to carbon dioxide: Complete combustion*

1. *Burning of Carbon monoxide to carbon dioxide : Intermediate combustion*
2. *Burning of sulphur to sulphur dioxide*

It is to be noted that in case of solid and liquid fuels, calculation is based on molar masses

1. **Combustion of Gaseous fuel**
2. *Burning of Carbon monoxide to carbon dioxide*
3. *Burning of gas to water vapour*
4. *Burning of methane gas*
5. *Burning of ethylene to carbon dioxide and water vapour*
6. *Burning of octane to carbon dioxide and water vapour*

It is to be noted that in case of gaseous fuels, calculation is based on volumes or number of moles

**3T’s for combustion**

The objective of a good combustion process is to ensure that the fuel will completely release heat during the reaction. This can be achieved by controlling the three T’s of combustion which are

1. temperature high enough to ignite and maintain ignition of the fuel,
2. turbulence for intimate mixing of the fuel and oxygen, and
3. time sufficient for complete combustion.

Too lean or too rich fuel in air leads to unburned fuel and carbon monoxide generation. Similarly too much excess air results in heat and efficiency losses [2]. Hence, stoichiometric ratio of fuel air mixture is required for complete combustion.

**Composition of dry air**

The major elements of dry air i.e., atmospheric air are O2, N2, CO2, argon. Compostion of dry air is shown below

|  |  |
| --- | --- |
| **Elements** | **% composition** |
| O2 | 20.95 |
| N2 | 78.09 |
| CO2 | 0.03 |
| Argon | 0.93 |

*Source: Thermal engineering, Rathore*

For all calculations, argon and CO2 are considered as an additional N2, because there are also inert gases like N2.

|  |  |  |
| --- | --- | --- |
| Basis | N2 (%) | O2 (%) |
| Volume or molar basis | 79 | 21 |
| Mass basis | 77 | 23 |

*Source: Thermal engineering, Rathore*

Thus with the above assumption value, the molar ratio of nitrogen to oxygen is. That means air supplied for combustion contains 3.76 mole of nitrogen with each mole of oxygen.

|  |  |
| --- | --- |
| **Molar basis** | **Mass basis** |
|  |  |
| 0.21 mole O2 + 0.79 mole N2 = 1 mole of air | 0.23 kg O2 + 0.77 kg N2 = 1 kg of air |
| i.e., 1 mole O2 + 3.76 mole N2 = 4.76 mole of air | i.e., 1 kg O2 + 3.347 kg N2 = 4.347 kg of air |
|  |  |
| Molecular weights | Mass of air = 28.97 kg/kmol |
| MO2 = 32, MN2 = 28 |

*Source: Thermal engineering, Rathore*

1. **Calculation of amount of air required for combustion (Solid fuel)**

A stoichiometric air or theoretical amount of air is a mix of fuel and air contains just enough oxygen to completely burn all the fuel elements (Carbon, hydrogen, sulphur).

The least possible amount of O2 required for combusting 1kg of fuel containing carbon, hydrogen and sulphur is shown below

1. *Burning of Carbon to carbon dioxide: Complete combustion*

*Using mass basis calculation*

Or

It means that 1kg of carbon requires kg of oxygen to produce kg of carbon dioxide.

Thus, C kg of carbon requires kg of oxygen

1. *Burning of sulphur to sulphur dioxide*

*Using mass basis calculation*

Or

It means that 1kg of sulphur requires 1 kg of oxygen to produce kg of sulphur dioxide.

Thus, S kg of carbon requires kg of oxygen

1. *Burning of gas to water vapour*

Or

Or

It means that 1kg of hydrogen requires 8 kg of oxygen to produce kg of water vapour. Thus, H kg of carbon requires kg of oxygen. From the above three equation, we can easily calculate the total oxygen requirement during burning of fuel

Total oxygen required = kg

Since, fuel contains oxygen (*O*), hence minimum amount of oxygen required for complete combustion is given by

Or

Since atmospheric air contains 23% of oxygen by mass. Therefore, minimum mass of air required is

=

1. **Calculation of amount of air required for combustion (Gaseous fuel)**

Let us consider 1m3 of gaseous fuel consisting of CO, H2, CH4, C2H4 etc. From the basic formula, the minimum air required for complete combustion of gaseous fuel can be calculated as follows

1. *Burning of Carbon monoxide to carbon dioxide*

*Using molar basis calculation*

Or

From the above equation it is found that 1 volume of CO requires to produce

1. *Burning of gas to water vapour*

*Using molar basis calculation*

Or

From the above equation, it can be inferred that requires for complete combustion to produce

1. *Burning of methane gas*

*Using molar basis calculation*

Or

It means that 1 m3 of CH4 combines with 2m3 of O2 to produce 1 m3 of CO2 and 2m3 of water vapour.

1. *Burning of ethylene to carbon dioxide and water vapour*

*Using molar basis calculation*

Or

It can be inferred that combines with to produce and

Thus, for complete combustion, amount of oxygen required is = *0.5 CO + 0.5 H2 + 2 CH4 + 3C2H4*

Since fuel contains O2, hence minimum amount of oxygen required for complete combustion is found out by subtracting the oxygen content in the fuel.

Therefore total amount of oxygen required = (*0.5 CO + 0.5 H2 + 2 CH4 + 3C2H4 ) - O2*

Again atmospheric air contains 21% of oxygen by volume. Hence, minimum volume of air required for complete combustion is

V*air* = (*0.5 CO + 0.5 H2 + 2 CH4 + 3C2H4 ) - O2*]

**Combustion of Oil**

Higher viscous oil is first preheated to get the desired viscosity before atomization is done. Boiler efficiency depends on the combustion system. Again combustion efficiency is an indication of the burner’s to burn the fuel completely. In order to burn 1 kg of fuel oil containing 86% carbon, 12% hydrogen, 2% sulphur, 14.1kg of air is required for complete combustion. A little amount of excess air is required for complete combustion of fuel. The products that are obtained from the reaction of fuel oil are CO2, SO2 and water vapour.

**Calculation of stoichiometric Air or theoretical air required**

***Question:*** *100kg of furnace oil has the following percentage composition by weight, 85.9% of carbon, 12% of hydrogen, 0.7% of oxygen, 0.5% nitrogen, 0.5% Sulphur, 0.35% water vapour and 0.05% ash. Given that the gross calorific value of furnace oil is 10880 kcal/kg. Calculate the theoretical air required for complete combustion.*

*Solution:*

1. Combustion of Carbon follows the equation

Or

Or

1. Burning of gas to water vapour

Or

Or

Or

(iii) *Burning of sulphur to sulphur dioxide*

*Using mass basis calculation*

Or

Or

Therefore total oxygen required = [ (

= 325.56 kg

Since 100kg of fuel already contains 0.7% of oxygen = 0.7 kg

Net oxygen required for combustion = (325.56 – 0.7) kg = 324.9 kg

Theoretical quantity of dry air required = 1412.60 kg

(since atmospheric air contains 23% of oxygen by weight)

Theoretical air required = kg of air/ kg of fuel

**Calculation of theoretical CO2** **content in flue gases**

Nitrogen present in the flue gas = (1414.60 – 324.9) kg = 1089.7 kg

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

Moles of CO2 in flue gas = = 7.15

Moles of N2 in flue gas = = 38.91

Moles of SO2 in flue gas = = 0.015

Theoretical CO2 % by volume =

=

= 15.5 %

**Calculation of constituents of flue gas with excess air**

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

% excess air =

=

= 55 %

Theoretical air required for burning 100 kg of fuel = 1414.60 kg

Total quantity of air supply required with 55% excess air = 1414.60 ×1.55 = 2192.63 kg

Excess air quantity = 2192.63 - 1414.60 = 778.03 kg

Oxygen = 778.03×0.23 = 178.94 kg

Nitrogen = (778.03-178.94) kg = 559.09 kg

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

|  |  |
| --- | --- |
| Constituent | Quantity (kg) |
| CO2 | 314.96 |
| O2 | 178.94 |
| N2 | 1648.79 |
| SO2 | 1 |
| H2O | 108 |

**Calculation of theoretical CO2 % in dry flue gas by volume**

Moles of CO2 in flue gas = = 7.15

Moles of N2 in flue gas = = 58.88

Moles of SO2 in flue gas = = 0.015

Moles of O2 in flue gas = = 5.59

Theoretical CO2 % by volume =

=

= 9.98 %

Theoretical O2 % by volume =

= 7.80 %

**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[1]

**Combustion of Coal**

Depending upon the constituent of coal i.e. carbon, hydrogen, nitrogen, oxygen and sulphur content, complete combustion of 1kg of coal requires 7 to 8 kg of air. This amount of air is known as theoretical or stoichiometric air. Incomplete combustion may be the cause for inadequate supply of air which results in smoke formation due to unburnt carbon. The product of combustion from incomplete combustion is CO, resulting in poor generation of heat. Complete combustion of coal can be achieved by passing excess air to the furnace. Excess supply of air is reqired for complete combustion. The excess air required for coal combustion depends on the type of coal firing equipment. Primary air is supplied below the grate. Ensuring complete combustion secondary air is supplied over the grate. 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 [1]

**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]

**Combustion 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, CH4. Its combustion can be represented as follows:

CH4 +2O2 = CO2 + 2H2O

So for every 16 kgs of methane that are consumed, 44 kgs of carbon dioxide are produced.

**Flue gas analysis**

Flue gas can be analyzed by passing through an arrangement which uses a chemical absorption technique to determine the mole fraction of CO, O2, CO2 in the fuel gas. The apparatus used for flue gas analysis is flue gas analyzer. Three pipettes are placed parallel to each other. First pipette contains containing cuprous chloride is used to absorb CO, the second pipette contains pyrogallic acid which is used to absorb O2 and the third pipette containing caustic soda(KOH) which will absorb CO2. The remaining gas obtained after absorbing is the N2. In order to get good results, the gas should be passed through proper sequence of the pipette as stated above. Orsat apparatus gives the volumetric analysis of dry flue gases, since steam is condensed at atmospheric temperature.

***Objectives:***

1. *Name the instrument used for the measurement of specific gravity of liquid fuel*

a) Gravimeter b) Hydrometer c) Bomb calorimeter d) none of the above

1. *The unit of specific gravity in SI system is*

a) N/m3  b) kgf/m3 c) kg/m2 d) no unit

1. *Presence of sulphur in the boiler fuel leads to*
2. corrosion b) erosion c) low heat transfer d) none of the above
3. *High percentage of carbon monoxide presence in the flue gas of boiler is an indicator of*

a) high excess air b) complete combustion c) good control of pollutants d) low excess air

1. *Which one of the following has a high specific gravity*

a) Furnace oil b) HSD c) Kerosene d) Water

1. *The main constituents of fuel are*
2. Hydrogen and oxygen (b) Carbon and hydrogen (c) Sulpur and hydrogen (d) Sulpur and Oxygen
3. *The amount of heat generated per kg fuel is known as*
4. Higher Calorific Value (b) Lower Calorific Value (c) Calorific value (d) None of the above
5. *Ultimate analysis of coal is done to determine the percentage of*
6. Carbon (b) Ash (c) Sulphur (d) Moisture
7. *A good fuel has*
8. Lower ignition point and higher calorific value
9. Lower ignition point and low calorific value
10. High ignition point and higher calorific value
11. High ignition point and low calorific value
12. *The symptom showing incomplete combustion of coal is*
13. Presence of free carbon in exhaust
14. Presence of oxygen in exhaust
15. Presence of free nitrogen in exhaust
16. Presence of carbon monoxide in exhaust

***Question:***

1. *Name the three main classification of coal.*
2. *What is the difference between Gross calorific value (GCV) and Net calorific value (NCV)?*
3. *What is the unit of viscosity? Name the instrument used for measurement of viscosity?*
4. *What is viscosity of liquid fuel oil?*
5. *What is the laboratory procedure for the measurement of Volatile matter for coal?*
6. *Give the empirical relationship to convert ‘proximate analysis’ to ‘ultimate analysis’ of with regard to coal.*
7. *Arrange the following fuels in the ascending order of their ‘calorific value’ (HSD, coal, paddy husk)*
8. *Define ‘density’ of a liquid fuel.*
9. *What is ‘excess air’ and why is it required for ‘combustion’ in a boiler?*
10. *Define ‘specific gravity’ for a fuel.*
11. *What is the main disadvantage of sulphur presence in any fuel?*
12. *Explain Storage, handling and preparation of coal.*
13. *Write the basic combustion equation*
14. *Explain the various stages of coal*
15. *Define stoichiometric air –fuel ratio.*

**References**

1. *Bureau of Energy efficiency*, [www.bee-india.nic.in](http://www.bee-india.nic.in), accessed on 28 June,2012
2. Rathore, M M; *Thermal Engineering*, Tata McGraw Hill, New Delhi, 2010
3. Speight, J.G.; *Handbook of coal analysis*, John Wiley & Sons, 2005
4. Sarkar, S.; *Fuel and Combustion*, Orient Longman Private Limited, 2003