Energy and Environmental Engineering

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Fuels & Properties

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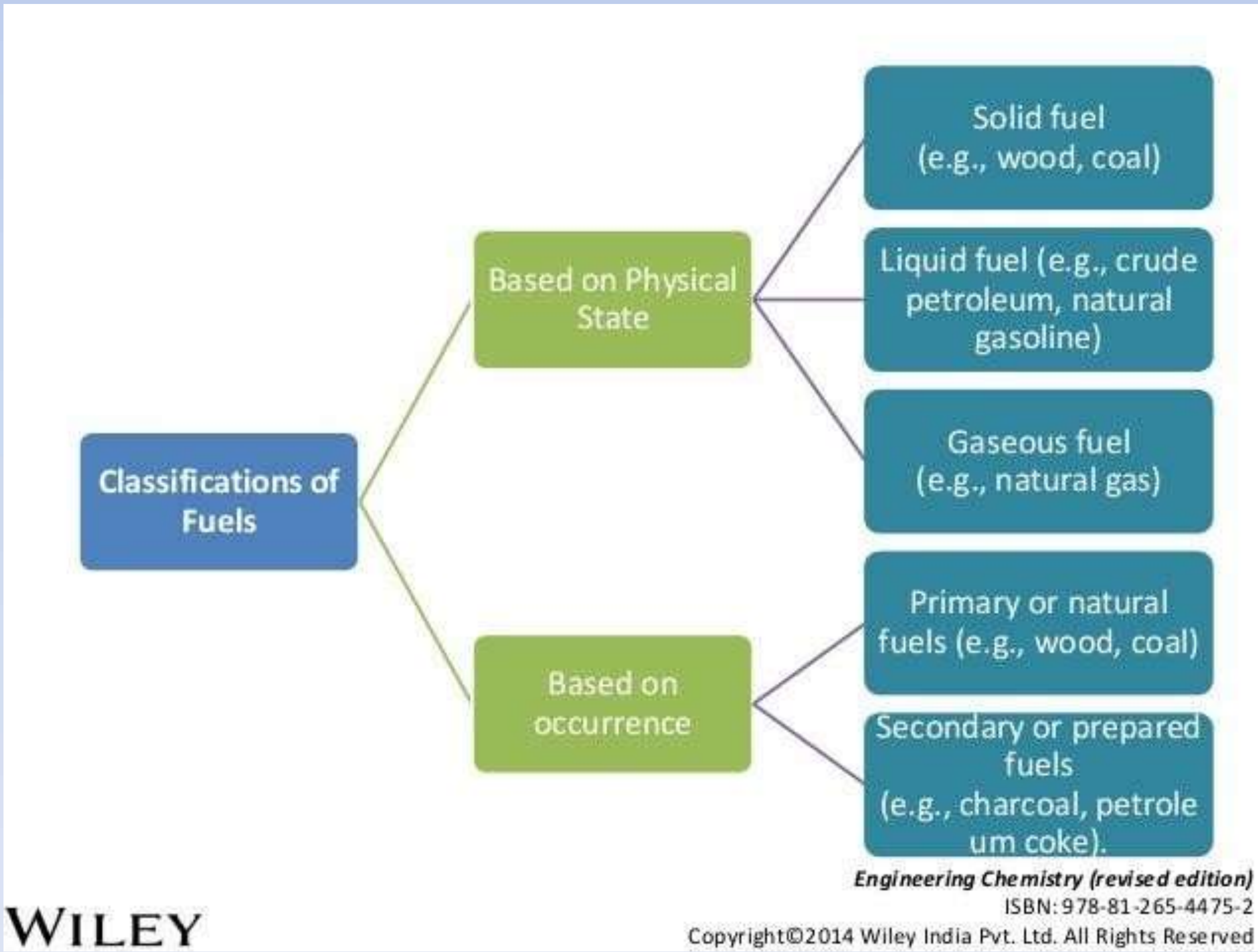
Fuels

- Fuel is any material that stores potential energy in a form that can be practicably released and used as heat energy
- Fuel may be chemical or nuclear (we will study briefly chemical fuels only)
- A chemical fuel is a substance which releases heat energy on combustion.
- Principal combustible elements of each fuel are carbon and hydrogen.

- Though sulphur is a combustible element too but its presence in the fuel is considered to be undesirable.
- Fuels are contrasted with other substances or devices storing potential energy, such as those that directly release electrical energy (such as batteries and capacitors) or mechanical energy (such as flywheels, springs, compressed air, or water in a reservoir).

Classification of Fuels



- Primary fuels are the ones which occur in nature
- While Secondary fuels are the prepared or derived fuels from the primary fuels.

Liquid Fuels

- Liquid fuels are combustible or energy-generating molecules that can be harnessed to create mechanical energy,
- Liquid fuels like furnace oil and LSHS (Low sulphur heavy stock) are predominantly used in industrial applications.
- Most liquid fuels in widespread use are derived from the fossil sources

- However, there are several types, such as hydrogen fuel (for automotive uses), ethanol, jet fuel and biodiesel which are all categorized as a liquid fuel.

Types of liquid fuels

1. Petroleum
2. Oils from distillation of petroleum
3. Coal tar
4. Shale-oil
5. Alcohols, etc.

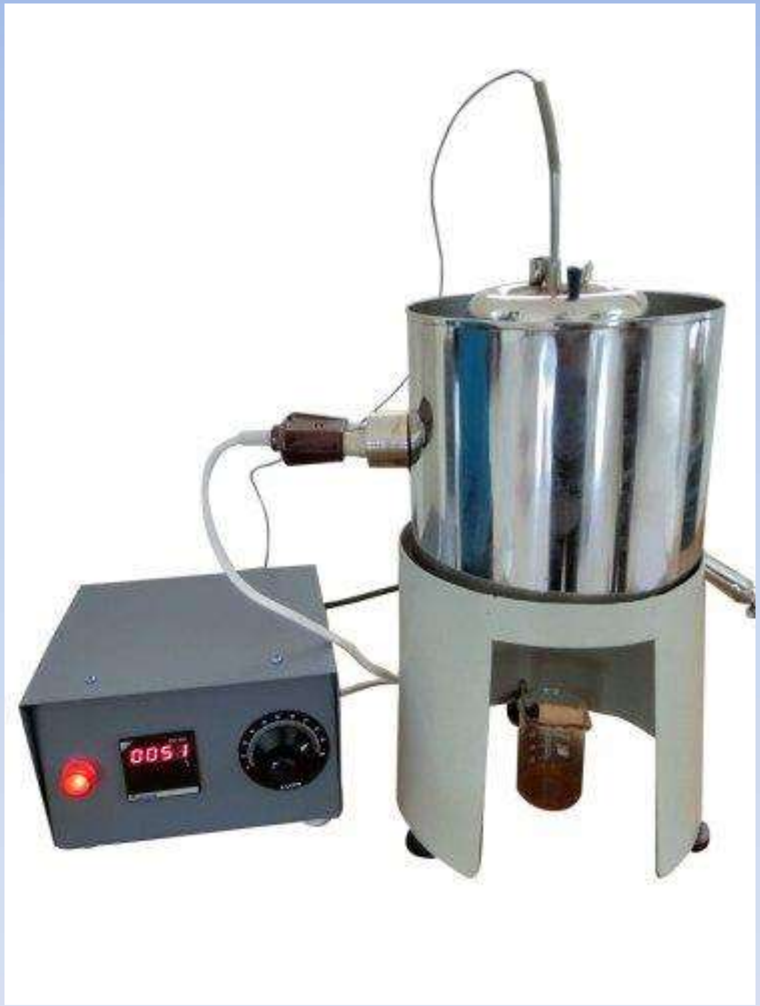
Properties of liquid fuels

- **DENSITY-**
  - Density is defined as the ratio of the mass of the fuel to the volume of the fuel at a reference temperature of 15°C.
  - The unit of measurement for density is kg/m3 and measured by a hydrometer.
  - It is important for assessing ignition qualities and other quantitative calculations.

Hydrometer

- **SPECIFIC GRAVITY**-
  - The specific gravity is a ratio, which 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.
  - E.g. Light diesel oil has specific gravity as 0.85 - 0.87, furnace oil has 0.89 - 0.95.

- **VISCOSITY-**
  - The viscosity of a fluid is a measure of its internal resistance to flow.
  - Viscosity depends on the temperature and decreases as the temperature increases.
- **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.
  - The 66 °C is the flash point for furnace oil.
- **FIREPOINT**



Redwood viscometer

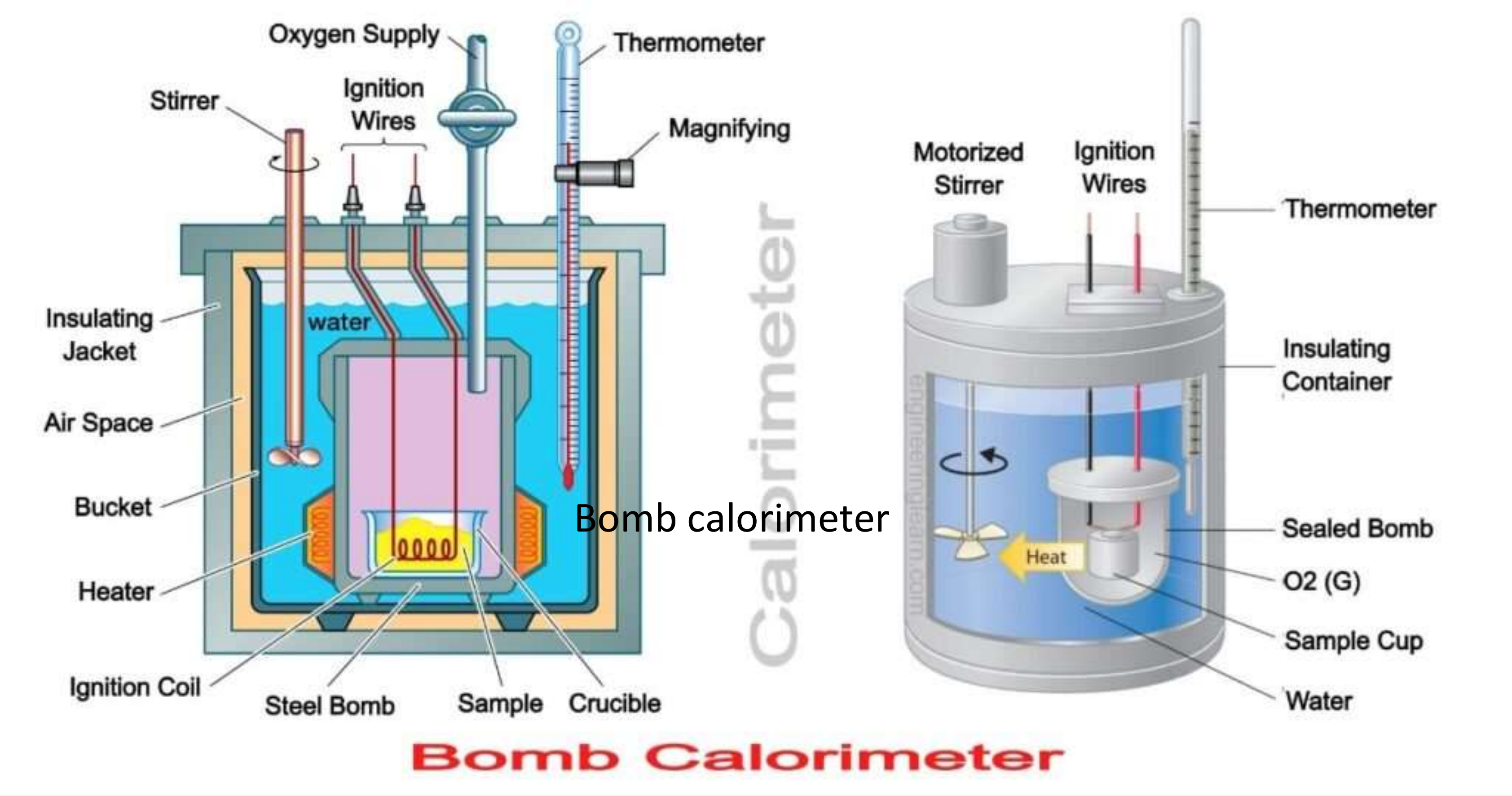
Flash and fire point apparatus

Cloud and pour point

- **POUR POINT-**
  - It is the fuel's lowest temperature at which it will pour or flow when cooled under prescribed conditions. It is a rough estimation of the lowest temperature at which fuel oil is ready to be pumped.
- **SPECIFIC HEAT-**
  - Specific heat is the amount of calories needed to raise the temperature of 1 kg of oil by 1^0C. The unit of specific heat is kcal/kg^{0}C. It varies from 0.22 to 0.28 depending on the oil specific gravity.

- **CALORIFIC VALUE-**
  - The calorific value measures the heat or energy produced. Gross calorific value (GCV) assumes all vapour produced during the combustion process is fully condensed and 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 fuel oils is much more consistent compare to coal (solid fuel), for example kerosene and diesel oil got the GCV 11,100 and 10,800 kCal/kg respectively.

* Multiply by 4.18 to convert kCal to kJ



Bomb calorimeter

A 1 g sample of fuel is burned in a bomb calorimeter containing 1.2 kg of water at an initial temperature of 25°C. After the reaction, the final temperature of the water is 33.2°C. The heat capacity of the calorimeter is 837 J/°C. The specific heat of water is 4.18 kJ/kg°C. The heat released by the fuel will be nearly

Concept:

- Since this is a combustion reaction, heat flows from the system to the surroundings, hence we can say that it is an exothermic reaction.
- The heat released by the reaction will be absorbed by two things: **(i)** the water in the calorimeter and **(ii)** the calorimeter itself.

Calculation:

The heat released by the fuel is given by mass of fuel multiplied by calorific value of the fuel

$\therefore M_f \times (C.V.) = m_w \times C_p \times \Delta T + C_{cal} \times \Delta T$

$= 1.2 \times 4.18 \times 10^3 \times (33.2°C - 25°C) + 837 \times (33.2°C - 25°C)$

$= 41131.2 + 6863.4 = 47994.6$ J

≈ 48000 J = 48 kJ

Hence when 1 g sample of fuel is burned the heat released by the fuel is 48 kJ/g.

... mass of condensate collected

h_{fg} = Latent heat of water at atmo. pressure

...(9.21.1) Volume flow rate of gases is converted at S.T.P i.e. at 25°C and 760 mm of Hg.

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f gaseous

9.21.1 : During Bomb calorimeter test on diesel oil, the following data were recorded :

Room temperature = 25°C

Weight of crucible = 8.231 gm

Weight of crucible and diesel oil = 8.803 gm

Weight of calorimeter vessel = 1.05 kg

Weight of water and calorimeter vessel = 3.5 kg

Water equivalent of calorimeter = 0.56 kg

Rise in temperature of water and calorimeter = 2.35°C

Cooling correction = 0.02°C

Find the HCV and LCV when mass of condensate is 0.32 gm.

The partial pressure of water vapour is 8 kPa.

Soln. :

Given : $T_0 = 25°C$

Weight of crucible, $m_{cr} = 8.231$ gm; Weight of crucible and oil = 8.803 gm

$\therefore$ Weight of oil, $m_o = 8.803 - 8.231 = 0.572$ gm

Weight of calorimeter vessel, $m_c = 1.05$ kg

Weight of water and calorimeter, $(m_w + m_c) = 3.5$ kg

$$\therefore m_w = 3.5 - 1.05 = 2.45 \text{ kg}$$

Water equivalent of calorimeter, $M_c = m_c \cdot C_{pc} = 0.56$ kg

$(\Delta T') = 2.35°C$; Cooling correction = 0.02°C

$\therefore$ Actual temperature rise of calorimeter and water,

$$\Delta T = \Delta T' + \text{Cooling correction} = 2.35 + 0.02 = 2.37°C$$

Mass of condensate, $m_{H_2O} = 0.32$ gm

Partial pressure of water vapour, $p_s = 8$ kPa = 0.08bar

(i) **H.C.V. of fuel, C :**

Heat given by fuel = Heat absorbed by water and calorimeter

$$m_o \times C = (m_w \times C_{pw} + m_c \cdot C_{pc})\,\Delta T$$

$$(0.572 \times 10^{-3}) \times C = (2.45 \times 4.187 + 0.56) \times 2.37$$

$$C = \mathbf{44823.5 \text{ kJ/kg of fuel}}$$ ...Ans.

ii) **LCV of fuel, C_1 :**

0.572×10^{-3} kg of oil forms the condensate $= 0.32 \times 10^{-3}$ kg

$\therefore$ 1 kg of oil will form condensate, $m_w = \dfrac{0.32 \times 10^{-3}}{0.572 \times 10^{-3}} = 0.5594$ kg/kg of oil

From steam tables at $p_s = 0.08$ bar we get :

$$h_g = 2577.1 \text{ kJ/kg}$$

Sensible heat of water of condensate at $(T_0 + \Delta T)°C$, i.e. at $(25 + 2.37)°C = 27.37°C$,

We get, $h_f = C_{pw} \times 27.37 = 4.187 \times 27.37 = 114.6$ kJ/kg

$\therefore$ Enthalpy given by vapour, $h = h_g - h_f = 2577.1 - 114.6 = 2462.5$ kJ/kg

$$\therefore \text{LCV of fuel} = \text{HCV of fuel} - m_w \times h$$

$$= 44823.5 \times 0.5594 \times 2462.5$$

$$= \mathbf{43446 \text{ kJ/kg}}$$ ...Ans.

Example 10.1. *The following particulars refer to an experimental determination of the calorific value of a sample of coal containing 88% C and 4.2% H_2. Weight of coal = 0.848 gm, weight of fuse wire 0.027 gm, of calorific value 6700 J/gm, weight of water in the calorimeter = 1950 gm, water equivalent of calorimeter = 380 gm, observed temperature rise = 3.06°C, cooling correction = + 0.017°C.*

Find the higher and lower calorific values of the coal.

Solution. Percentage of *carbon* in coal = 88%

Percentage of *hydrogen* in coal = 4.2%

Weight of coal, $w_f = 0.848$ gm

Weight of fuse wire, $w_{fw} = 0.027$ gm

Weight of water in the calorimeter, $w = 1950$ gm
Water equivalent of calorimeter, $w_e = 380$ gm
Observed temperature rise $(t_2 - t_1) = 3.06°C$
Cooling correction,

$$t_c = +\ 0.017°C$$

$\therefore$ Corrected temperature rise

$$= (t_2 - t_1) + t_c$$
$$= 3.06 + 0.017 = 3.077°C$$

Calorific value of fuse wire

$$= 6700 \text{ J/gm}$$

Heat received by water

$$= (w + w_e) \times 4.18 \times [(t_2 - t_1) + t_c]$$
$$= (1950 + 380) \times 4.18 \times 3.077$$
$$= 29968 \text{ J}$$

Heat given out by fuse wire

$$= w_{fw} \times \text{calorific value}$$
$$= 0.027 \times 6700 = 180.9 \text{ J}$$

Heat produced due to combustion of fuel

$$= 29968 - 180.9 = 29787.1 \text{ J}$$

$\therefore$ *Higher calorific value of fuel, H.C.V.*

$$= \frac{29787}{0.848} = 35126 \text{ J/gm}$$
$$= \mathbf{35126\ kJ/kg.} \quad \text{(Ans.)}$$

Steam produced per kg of coal

$$= 9 \times 0.042 = 0.378 \text{ kg}$$

Lower calorific value of coal, L.C.V.

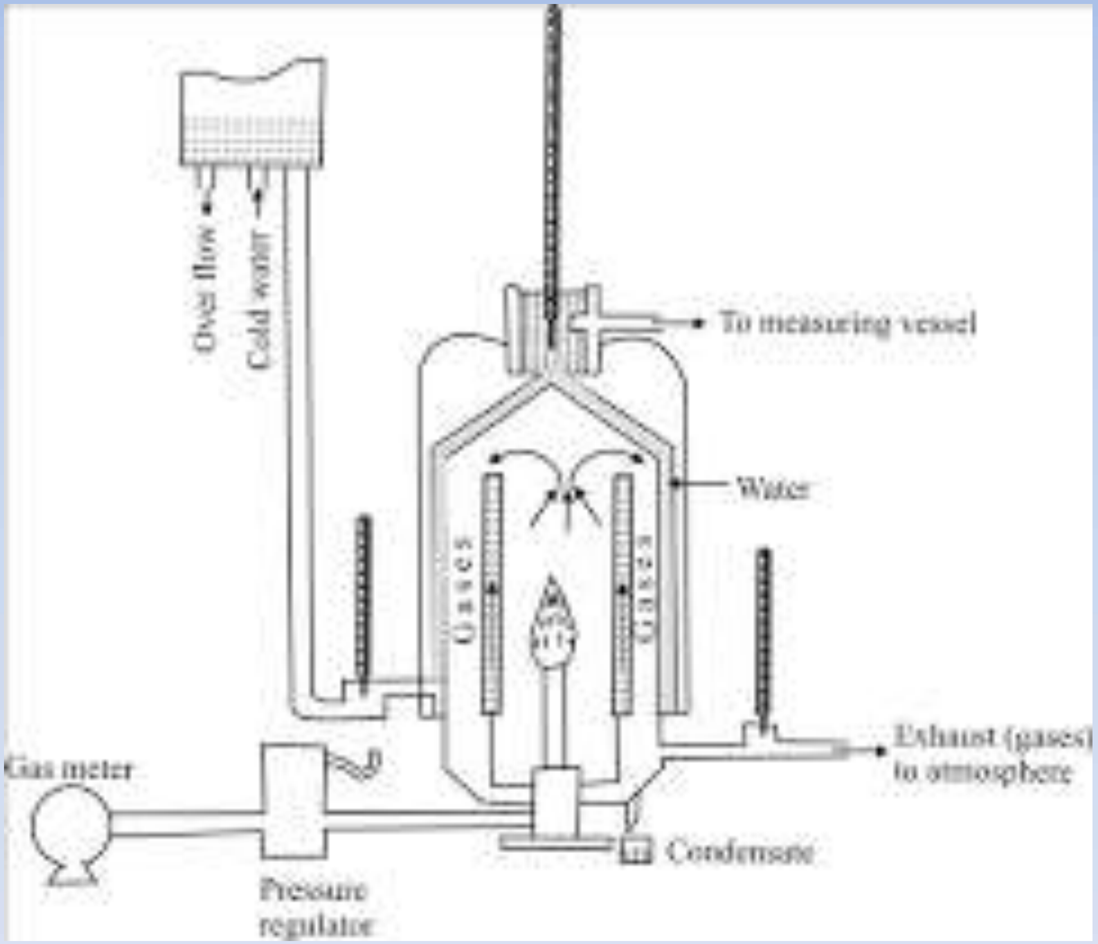
$$= \text{H.C.V.} - 2465 \times 0.378$$
$$= 35126 - 931.7$$
$$= \mathbf{34194.3\ kJ/kg.} \quad \text{(Ans.)}$$

10.19.2. Gaseous Fuels

The calorific value of gaseous fuels can be determined by ***Junker's gas calorimeter.***

Fig. 10.6 illustrates *Junker's gas calorimeter.* Its principle is some what similar to Bomb calorimeter, in respect that heat evolved by burning the gas is taken away by the water. In its simplest construction it consists of a combustion chamber in which the gas is burnt (in a gas burner). A water jacket through which a set of tubes called flues pass surrounds this chamber. Thermometers are incorporated at different places (as shown in Fig. 10.6) to measure the temperatures.

Procedure. A metered quantity of gas whose calorific value is to be determined is supplied to the gas burner via a gas meter which records its volume and a gas pressure regulator which measures the pressure of the gas by means of a manometer. When the gas burns the hot products of combustion travel upwards in the chamber and then downwards through the flues and finally escape to the atmosphere through the outlet. The temperature of the escaping gas is recorded by the thermometer fitted at



Junkers Gas Calorimeter

Note 1. The volume of gas used during the experiment should be converted to volume at S.T.P. (standard temperature and pressure *i.e.*, 15°C, 760 mm respectively).

2. The gross calorific value is obtained by dividing the heat given out by corrected volume of gas. The net or lower calorific value of the gas is obtained by subtracting from total heat the heat associated with condensed water (which is obtained by multiplying the weighed condensate by latent heat of vaporisation of water.).

Example 10.2. *Following results were obtained when a sample of gas was tested by Junker's gas calorimeter :*

Gas burnt in the calorimeter = 0.08 m^3, Pressure of gas supply = 5.2 cm of water, Barometer = 75.5 cm of Hg. Temperature of gas = 13°C, Weight of water heated by gas = 28 kg, Temperature of water at inlet = 10°C, Temperature of water at outlet = 23.5°C, Steam condensed = 0.06 kg.

Determine the higher and lower calorific values per m^3 of the gas at a temperature of 15°C and barometric pressure of 76 cm of Hg.

Solution. The volume of the gas is measured at a temperature of 13°C and pressure of 5.2 cm of water. Let us reduce this volume to S.T.P. by using the general gas equation,

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

$$p_1 = 75.5 + \left(\frac{5.2}{13.6}\right) = 75.882 \text{ cm of Hg ;}$$

$$T_1 = 273 + 13 = 286 \text{ K}$$

$$V_1 = 0.08 \text{ m}^3 \text{ ; } p_2 = 76 \text{ cm of Hg}$$

$$V_2 = ? \text{ ; } T_2 = 273 + 15 = 288 \text{ K}$$

$$\therefore \quad \frac{75.882 \times 0.08}{286} = \frac{76 \times V_2}{288}$$

i.e.,
$$V_2 = \frac{75.882 \times 0.08 \times 288}{286 \times 76} = 0.0804 \text{ m}^3$$

Heat received by water

$$= 28 \times 4.18 \times (23.5 - 10) = 1580 \text{ kJ}$$

Higher calorific value of fuel

$$= \frac{1580}{0.08} = \mathbf{19750 \text{ kJ/m}^3}. \quad \textbf{(Ans.)}$$

Amount of water vapour formed (*i.e.*, steam condensed)

per m^3 *of gas burnt* $= \dfrac{0.06}{0.08} = 0.75$ kg

Lower calorific value, L.C.V.

$$= \text{H.C.V.} - 2465 \times 0.75$$

$$= 19750 - 1848.7 = \mathbf{17901.3\ kJ/kg.}$$ **(Ans.)**

HCV VERSUS LCV

HCV	LCV
Amount of heat evolved when a unit weight (or volume in the case of gaseous fuels) of the fuel is completely burnt and the products of combustion cooled to the normal conditions (with water vapor condensed as a result)	Amount of heat evolved when a unit weight (or volume in the case of gaseous fuels) of the fuel is completely burnt and water vapor leaves with the combustion products without being condensed
Also known as higher heating value (HHV) or gross calorific value	Also known as lower heating value (HHV) or net calorific value
Total energy released when products have cooled down to the room temperature and water has been condensed out	Energy released when products are hot
Byproducts are allowed to condense	Byproducts are allowed to escape
Some of the heat or energy in byproducts can be recovered through condensation	Heat or energy in byproducts escapes the system
High value	Low value

- **SULPHUR-**
  - The amount of sulphur in the fuel oil depends on the source of the crude oil and on the refining process.
  - The sulphur content for the residual fuel oil is in the order of 2 - 4 %.
- **CARBON RESIDUE-**
  - Carbon residue indicates the tendency of oil to deposit a carbonaceous solid residue on a hot surface like burner and injection nozzle when its vaporizable constituents evaporate.
  - The residual oil contains carbon residue of 1% or higher.

- **ASH CONTENT-**
  - The ash value is related to the inorganic material or salts(compounds of sodium, vanadium, calcium, magnesium, silicon, iron, aluminum, nickel etc.) in the fuel oil and ash levels in distillate fuels are negligible. the residual fuels have higher ash levels.
  - The ash has an erosive effect on the burner tips, causes damage to the refractories at high temperatures and gives rise to high temperature corrosion and fouling of equipment's.

- **WATER CONTENT-**
  - The water content are low when it is supplied because the product at refinery site is handled hot, the water content can be maximum 1% which the upper limit.
  - The water content can cause damage to the inside surfaces of the furnace during combustion especially if it contains dissolved salts or it can cause spluttering of the flame at the burner tip, possibly extinguishing the flame, reducing the flame temperature or lengthening the flame.

Advantages of Liquid Fuels

1. They posses higher calorific value per unit mass than solid fuels.
2. They burn without dust, ash, clinkers, etc.
3. Their firing is easier and also fire can be extinguished easily by stopping liquid fuel supply.
4. They are easy to transport through pipes.
5. They can be stored indefinitely without any loss.
6. They are clean in use and economic to handle.
7. Loss of heat in chimney is very low due to greater cleanliness.
8. They require less excess air for complete combustion.
9. They require less furnace space for combustion.

Disadvantages of liquid fuel

1. The cost of liquid fuel is relatively much higher as compared to solid fuel.
2. There is a greater risk of fire hazards, in case of highly inflammable and volatile liquid fuels.
3. They give bad odour.
4. Special storage tanks are required for storing liquid fuels.
5. Specially constructed burners and spraying apparatus are required for efficient burning of liquid fuels.

Gross calorific values for different fuel oils

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

* Multiply by 4.18 to convert kCal to kJ

Solid Fuels

- Solid fuel refers to various types of solid material that are used as fuel to produce energy and provide heating, usually released through combustion.
- Solid fuels are mainly classified into two categories, i.e. natural fuels, such as wood, coal, etc. and manufactured fuels, such as charcoal, coke, briquettes, etc.
- Coal is classified into three major types; anthracite, bituminous, and lignite.

Solid Fuels

- Coal is further classified as semi-anthracite, semi-bituminous, and sub-bituminous.
- Anthracite is the oldest coal from a geological perspective. It is a hard coal composed mainly of carbon with little volatile content and practically no moisture.

Solid Fuels

- Types of solid fuel
    1. Wood
    2. Coal
    3. Oil shale
    4. Tanbark
    5. Bagasse
    6. Straw
    7. Charcoal
    8. Coke
    9. Briquettes

Solid Fuels

- **Anthracite**
  - It is very hard coal and has a shining black lustre.
  - It is non-caking and has high percentage of fixed carbon.
  - The calorific value of this fuel is high to the tune of 35500kJ/kg and as such is very suitable for steam generation

Solid Fuels

- **Bituminous**
  - It burn with long yellow and smoky flames and high percentage of volatile matter.
  - The average calorific value of bituminous coal is about 31350 kJ/kg.
  - It may be of two types –caking and non-caking.

Solid Fuels

- **Lignite OR brown coals**
  - These are intermediate stages between peat and coal.
  - They have a woody or often a clay like appearance associated with high moisture, high ash and low heat contents.
  - Lignite are usually amorphous in character and impose transport difficulties as they break easily. They burn with a smoky flame. Some of this type are suitable for local use only.

- **Lignite OR brown coals**

Wood

- The woods are very easily available and most commonly used solid fuel.
- The woods are used as fuel from ancient time after the discovery of the fire.
- The wood is used for industrial purposes. Constituents of Wood is vegetable tissue of trees and bushes.
- The wood consists of mainly cellular tissue & lignin. It also consists of lesser parts of fat & tar and sugar.

Woo d

- Wood mainly consists of carbon and Hydrogen.
- The wood is converted into coal when burnt in absence of air.
- The average value calorific value of the wood is 19700 kJ/kg.

Advantages of Solid fuels

- Easier transportation and storage.
- Low production cost.
- Moderate ignition temperature.

Disadvantages of solid fuel

- Large portion of energy is wasted.
- Cost of handling is high and controlling is also hard.
- Ash content is high & burn with clinker formation.

Gaseous fuels

- Gaseous fuels may be divided into four classes: natural gas, producer gas, water gas and coal gas.(SynGas/Synthesis gas)

Producer gas is the product obtained when coal or coke is burnt with air deficiency and with a controlled amount of moisture.

Syngas, or synthesis gas, is **a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very** often some carbon dioxide. ... Syngas is usually a product of coal gasification and the main application is electricity generation. Syngas is combustible and can be used as a fuel of internal combustion engines

Merits of gaseous fuels

- Economy in **fuel** and extra efficiency of engine.
- This is compressible, and therefore, storage will be easier.
- A large amount less air is required for complete combustion.
- Less Starting troubles and freezing problems are remove.
- A **gaseous fuel** can simply carried through pipes.
- Engine can be run with Lean mixture.

Demerits of gaseous fuels

- Purification cost is elevated
- Storage capacity per unit energy is reasonably extremely large
- High cost and size and weight of engine are reasonably large

Requirement of good fuel

1. It should have a high calorific value i.e., it should evolve a large amount of heat when it is burnt.
2. Its moisture content should be low so that its heating value should be high.
3. An ideal fuel should have moderate ignition temperature.
4. It should not produce harmful products like CO_2,, SO_2,, H_2S and other poisonous gases on burning since they pollute the atmosphere

Requirement of good fuel

5. A fuel should have low content of non-combustible matter in the form of ash or clinker. Since the presence of non-combustible matter will enhance the cost of storage, handling and disposal of waste.
6. The combustion of fuel should be controllable so that it can be started or stopped.
7. It should not give any offensive odour.
8. It should have moderate velocity of combustion

Calorific Value of fuels

- Higher or Gross CV
  - The amount of heat obtained by the complete combustion of 1 kg of fuel, when the products of its combustion are cooled down to the temperature of air supplied (usually taken as 15^oC), is called the gross or higher calorific value.
- Lower or Net CV
  - When the heat absorbed or carried away by the products of combustion is not recovered and the steam formed during combustion is not condensed

Carbon value of fuels

- The number of kgs of carbon required to produce the same amount of heat as one kg of fuel is known as the carbon value of fuel and is given by the relation:

$$Carbon\ value\ of\ fuel = \frac{C.V\ of\ fuel}{C.V\ of\ carbon}$$

Estimation of calorific value

- Dulong's formula

$$H.C.V. = 33800C + 144000\left(H_2 - \frac{O_2}{8}\right) + 9270S, kJ/kg$$

$$L.C.V. = H.C.V. - Heat\ of\ steam\ formed\ during\ combustion$$

$$L.C.V. = H.C.V. - (9H_2 \times 2466)$$

- By actual experiments
  - Bomb calorimeter
  - Boys calorimeter

Proximate and Ultimate analysis

- Proximate:
  a. moisture,
  b. ash,
  c. volatile matter, and
  d. fixed carbon
- Ultimate
  - major organic **elemental** composition
  - C, H, N, S, O

Proximate vs Ultimate Analysis of Coal

	Proximate Analysis	Ultimate Analysis
DEFINITION	Proximate analysis of coal is the determination of the presence of different compounds and their amounts in coal	Ultimate analysis of coal is the determination of different chemical elements present in coal
DETERMINATION	Composition of coal according to moisture content, ash content and fixed carbon content	Elemental composition of coal
ACCURACY	Low	High

No.	Parameter	Sanbi Coal (Japan)
	Proximate analysis/(wt %)	
1	Fixed moisture	2.10
2	Ash content	4.30
3	Volatile matter	43.10
4	Fixed carbon	50.50
5	Total sulfur	0.07
	Ultimate analysis/(wt %)	
6	Carbon	78.40
7	Hydrogen	5.74
8	Nitrogen	1.44
9	Oxygen	9.94

1.6 Proximate and Ultimate Analysis

- **Proximate analysis** of coal examines the chemical composition of a coal sample**.**

  Moisture, Volatile compounds, Ash content, Fixed carbon.

  Proximate analysis used to ascertain "Rank" of coals as the above parameters will indicate the Heating value of the coal.

- **Ultimate analysis** - It is more comprehensive, is dependent on quantitative analysis of various elements present in the coal sample such as

  carbon, hydrogen, sulfur, oxygen, and nitrogen.

Combustion of fuel

- $C+O_2=Co_2$
- $C_xH_y+O_2=CO_2+H_2O$

	$2H_2 + O_2 \rightarrow$		$2\ H_2O$
Molecular weight	$2x2 + 32 \rightarrow$		$2x18$
$\Rightarrow$	$1 + 8$	$\rightarrow$	9
i.e.	1 kg of H_2 + 8 kg of O_2	$\rightarrow$	9 kg of H_2O