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Excerpt
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Chapter 1
FUELS

1.1 Introduction

A fuel is a substance that produces useful energy either through combustion or through nuclear reaction. An important property of a fuel is that the energy is released in a controlled manner and can be harnessed economically for domestic and industrial purposes. Wood, coal, charcoal, petrol, diesel, kerosene, producer gas and oil gas are some of the common examples of fuels.

Fuels that produce heat energy by combustion are termed as *chemical fuels*. During combustion, carbon, hydrogen, sulphur and phosphorus that are present in the fuel combine with oxygen and release energy.

$$\text{Fuel} + O_2 \rightarrow \text{Products} + \text{Heat}$$

$$C + O_2 \rightarrow CO_2 + \text{Heat}$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat}$$

However, combustion is not always necessary for a fuel to produce heat. Energy can also be liberated by fission or fusion of nuclei. This energy is much greater than the energy released by chemical fuels, and such fuels are termed as *nuclear fuels*. For example, plutonium, tritium, uranium, etc.

1.2 Classification of Fuels

Fuels can be classified on the basis of their (I) Occurrence (II) Physical State

(I) On the basis of occurrence, fuels are of two types

(a) **Primary Fuels or Natural Fuels** These are found to occur in nature and are used as such either without processing or after being processed to a certain extent, which does not alter the chemical constitution of the fuel. These are also known as fossil fuels. Examples include wood, peat, lignite, coal, petroleum, natural gas, etc.

(b) **Secondary Fuels or Derived Fuels** These are the fuels that are derived from primary fuels by further chemical processing; for example, coke, charcoal, kerosene, producer gas, water gas, etc

(II) On the basis of their physical state, fuels may be classified as follows

(a) Solid fuels

(b) Liquid fuels

(c) Gaseous fuels

The classification can be summarized as

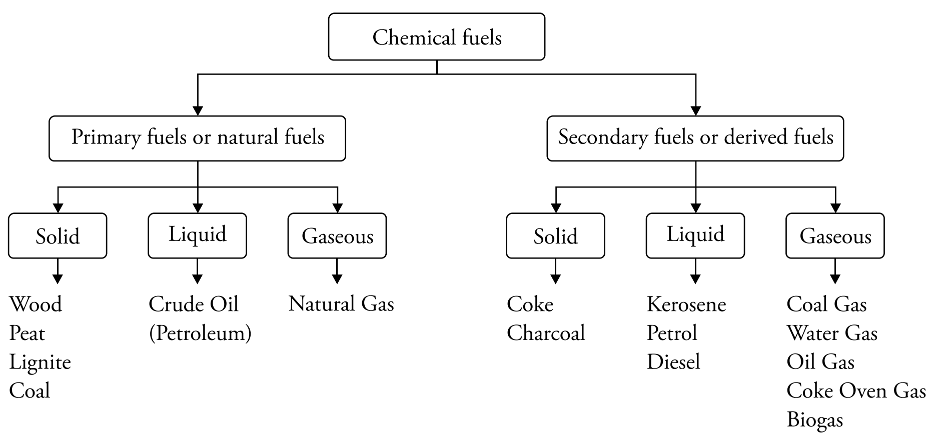

Figure 1.1 *Classification of fuel*

1.3 Characteristics of a Good Fuel

1. ***High Calorific value*** A good fuel should possess high calorific value because calorific value determines the efficiency of the fuel. Higher the calorific value greater is the heat liberated per unit mass or volume.
2. ***Ignition Temperature*** It is the lowest temperature to which a fuel must be preheated so that it starts burning smoothly. An ideal fuel should have moderate ignition temperature. Low ignition temperature can cause fire hazards, making storage and transportation difficult. Fuel with low ignition temperature can burn spontaneously leading to explosion. High ignition temperature, on the other hand, makes it difficult to kindle (ignite) the fuel.
3. ***Moisture Content*** Moisture content should be low because the presence of moisture lowers the calorific value of the fuel.

4. ***Non–combustible matter*** After combustion, the non-combustible matter is left behind as ash or clinkers. Non-combustible matter reduces the calorific value of the fuel and also requires additional money investment for storage, handling and disposal of the waste products produced.
5. ***Velocity of combustion*** If the velocity of combustion is low, then a part of the liberated heat may get radiated instead of raising the temperature; hence, the required high temperature may not be attained. On the other hand, if the velocity of combustion is very high then the rate of combustion might become uncontrollable. For a continuous supply of heat, fuel must burn with a moderate rate.
6. ***Combustion products*** The products obtained during combustion of the fuel should be harmless and non-polluting. Harmful gases such as CO_2, SO_2, H_2S, PH_3 and $PbBr_2$ should not be produced, and also the amount of smoke produced should be less.
7. ***Cost of the fuel*** A good fuel should be readily available at a low cost.
8. ***Storage and transportation*** A good fuel should be easy to handle, store and transport at low cost.
9. ***Size*** In case of solid fuels, the size should be uniform so that combustion is regular.
10. ***Combustion should be controllable*** The combustion process should be controllable, i.e., it can be started or stopped when required.

Table 1.1 Comparison of solid, liquid and gaseous fuel

S.No.	Solid Fuel	Liquid Fuel	Gaseous Fuel
1	Cheap and easily available.	Costlier than solid fuel except in the countries of origin.	Costly, because except natural gas all other gaseous fuels are derived from solid and liquid fuels.
2	Convenient to store without any risk of spontaneous explosion.	Great care must to be taken to store them in closed containers.	Very large storage tanks are needed. Storing gaseous fuel requires extra care as they are highly inflammable.
3	Large space is required.	Storage space is less compared with solid and gaseous fuels.	They must be stored in leak proof containers.
4	They are easy to transport.	They can be easily transported through pipelines.	They can also be transported through pipelines.
5	They posses moderate ignition temperature. Combustion is slow but it cannot be controlled easily.	Combustion takes place readily and can easily be controlled or stopped by reducing or stopping the fuel supply.	Combustion is fast and can be controlled and stopped easily.
6	Ash is produced and its disposal is a big problem. Smoke is also produced.	Ash is not produced, however fuels with high carbon and aromatic contents may produce smoke.	Neither ash nor smoke is produced.
7	They cannot be used in internal combustion engine.	Used in internal combustion engine (petrol, diesel).	Used in internal combustion engines (CNG,LPG)

8	They have low thermal efficiency.	Their thermal efficiency is higher than solid fuels.	Their thermal efficiency is highest.
9	Their calorific value is lowest.	Their calorific value is higher than solid fuels.	Their calorific value is the highest.
10	Least risk of fire hazards.	Risk of fire hazards is high.	Highest risk of fire hazards.

1.4 Calorific Value

It is defined as the total amount of heat liberated when a unit mass or volume of fuel is burnt completely.

Units of heat

(i) ***Calorie*** It is defined as the amount of heat required to raise the temperature of 1 g of water by 1°C (from 15°C to 16°C)

1 Calorie = 4.185 Joules = 4.185×10^7 Ergs.

(ii) ***Kilocalorie*** It is defined as the amount of heat required to raise the temperature of 1 kg of water by 1°C (from 15°C to 16°C). 1 Kcal = 1000 Cal

(iii) ***British Thermal Unit*** (*B.T.U*). It is defined as the amount of heat required to raise the temperature of 1 Pound (lb) of water by 1 °F (from 60° F to 61° F)

1 B.T.U = 252 Cal = 0.252 Kcal = 1054.6 Joule = 1054.6×10^7 Ergs.

(iv) ***Centigrade Heat Unit*** (*C.H.U*). It is defined as the amount of heat required to raise the temperature of one pound of water by 1°C (from 15°C to 16°C).

1 Kcal = 3.968 B.T.U. = 2.2 C.H.U.

Units of calorific value

The units of calorific value for solid, liquid and gaseous fuels are given below.

System	Solid / Liquid fuels	Gaseous fuels
CGS	calories/gm	calories/ cm^3
MKS	Kcal/Kg	Kcal/m^3
BTU	B.T.U./lb	B.T.U./ ft^3

These units can be interconverted as follows

1 cal/g =1 Kcal/kg = 1.8 B.T.U./lb

1 Kcal = 0.1077 B.T.U./ft^3

1 B.T.U. /ft^3 = 9.3 Kcal/m^3

Gross and Net Calorific Value

Gross Calorific Value (***GCV***) It is also called higher calorific value (HCV) and is defined as the total amount of heat produced when a unit quantity (mass/volume) of fuel is burnt completely, and the products of combustion are cooled to room temperature.

Usually all fuels contain hydrogen. During combustion, the hydrogen present in the fuel is converted into steam. When the combustion products are cooled to room temperature, the steam gets condensed into water and heat that equals the latent heat of condensation of steam is evolved. This heat gets included in the measured heat, and so its value is high; hence, it is called higher calorific value.

Low Calorific Value (***LCV***) It is also termed as net calorific value (NCV) and is defined as the heat produced when a unit quantity (mass/volume) of a fuel is burnt completely and the hot combustion products are allowed to escape.

In actual practice, when a fuel is burnt water vapor escapes along with the hot combustion gases; hence, heat available is lesser than the gross calorific value. Therefore, this is called low calorific value (LCV) or net calorific value (NCV).

Thus LCV = HCV – Latent heat of water vapour formed.

As 1 part by weight of hydrogen gives 9 parts by weight of water,

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

LCV = HCV – Weight of hydrogen in fuel × 9 × latent heat of steam

Solved Examples

1. 2 kg of a coal sample was burnt in a bomb calorimeter. The heat liberated was estimated and found to be 14114 Kcal. Calculate the calorific value of the coal sample.

Solution

Heat liberated on burning 2 Kg coal = 14114 Kcal.

Therefore, heat liberated on combustion of 1 Kg coal = $\frac{14114}{2} = 7057$ Kcal.

[Ans Calorific value of coal = 7057 Kcal/kg].

2. The gross calorific value of a fuel containing 8% hydrogen was found to be 9225.9 Kcal/kg. Find out its net calorific value if the latent heat of steam is 587 Kcal/kg.

Solution

NCV = GCV – 0.09 H × Latent heat of steam.

NCV = 9225.9 – 0.09 × 8 × 587.

= 9225.9 – 422.64 = 8803.26 Kcal/kg

[Ans LCV/NCV = 8803.26 Kcal/kg].

Practice problems

1. Calculate the GCV of a coal sample if its LCV is 6767.45 cal/g and if it contains 5% hydrogen. (Latent heat of steam is 587 cal/g).

   [Ans GCV = 7031.6 cal/g].

2. The gross calorific value of a fuel containing 6% H was found to be 9804.6 Kcal/kg. Find the net calorific value if the latent heat of steam is 587 cal/g.

   [Ans 9487.62 Kcal/Kg].

Determination of Calorific Value

The calorific value of solid and non-volatile liquid fuels is determined by Bomb Calorimeter, whereas the calorific value of gaseous fuels is determined by Junkers Calorimeter.

Bomb calorimeter

Principle A known amount of fuel is burnt in excess of oxygen and the heat liberated is absorbed in a known amount of water. This heat liberated is measured by noting the change in temperature. Calorific value of the fuel is then calculated by applying the following principle

Heat liberated by fuel = Heat absorbed by water and the calorimeter.

Construction A simple sketch of the bomb calorimeter is shown in the Fig. 1.2 given below.

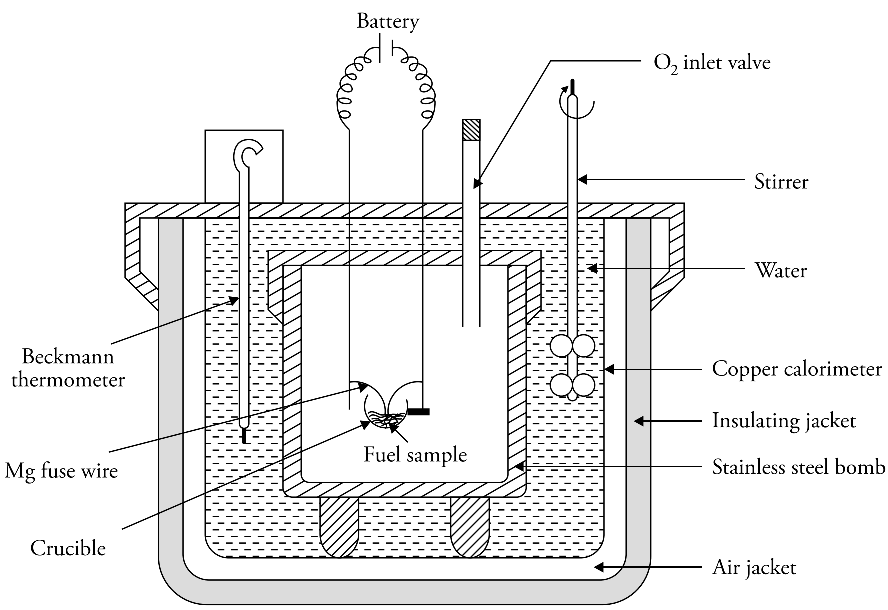

Figure 1.2 *Bomb calorimeter*

It consists of the following parts

(i) ***Stainless steel bomb*** It consists of a long cylindrical container made up of stainless steel. It has a lid that is made air tight with the help of screws. The lid is provided with two holes for electrodes and has an oxygen inlet valve. A small ring is attached to one of the electrodes. This ring acts as a support for nickel or stainless steel crucible in which the fuel is burnt. Magnesium wire touching the fuel sample extends across the electrodes. The steel bomb is lined inside with platinum to resist corrosive action of HNO_3 and H_2SO_4 vapors formed because of burning of fuel and is designed to withstand high pressure (25–50 atm).

(ii) ***Copper calorimeter*** The bomb is placed in a copper calorimeter containing a known amount of water. The calorimeter is provided with an electrical stirrer and a Beckmann thermometer that can read accurate temperature difference of up to $1/100^{th}$ of a degree.

(iii) ***Air jacket and water jacket*** The copper calorimeter is surrounded by an air jacket and a water jacket to prevent loss of heat owing to radiation.

Working A known amount of fuel (0.5–1 g) is taken in a clean crucible supported over the ring. A fine magnesium wire, touching the fuel sample, is then stretched across the electrodes. About 10 ml of distilled water is introduced into the bomb to absorb vapors of sulphuric acid and nitric acid formed during combustion, and the lid of the bomb is tightly screwed. The bomb is filled with oxygen at 25 atmospheric pressure and placed in the copper calorimeter containing a known weight of water. The stirrer is started and the initial temperature of water is noted. The electrodes are then connected to a 6-volt battery to complete the circuit. The sample burns and heat is liberated. This heat is absorbed by water. Maximum temperature shown by the thermometer is recorded. Time taken to cool the water in the calorimeter from maximum temperature to room temperature is also noted. The gross calorific value of the fuel is calculated as follows.

Calculations

Let,

Weight of fuel sample taken	= x gm.
Weight of water in the calorimeter	= W gm.
Water equivalent of calorimeter, stirrer, thermometer, bomb etc	= w gm.
Initial temperature of water in the calorimeter	= t_1°C.
Final temperature of water in the calorimeter	= t_2°C.
Higher calorific value of fuel	= H calorie / gm.
Heat liberated by burning of fuel	= $x \times$ H.
Heat gained by water	= W × ΔT × specific heat of water.
	= W $(t_2 - t_1) \times 1$ cal.
Heat gained by calorimeter	= w $(t_2 - t_1)$.
Total heat gained	= W $(t_2 - t_1)$ + w $(t_2 - t_1)$.
	= (W + w) $(t_2 - t_1)$.

But,

Heat liberated by the fuel = Heat absorbed by water and calorimeter.

$$x \times H = (W + w)(t_2 - t_1)$$

$$H = \frac{(W + w)(t_2 - t_1)}{x} \text{ cal/gm (or Kcal/Kg)}$$

Net (lower) calorific value
LCV = HCV – 0.09H × 587 cal/gm or Kcal/Kg
(Latent heat of condensation of steam = 587 Kcal/Kg)

Corrections

Following corrections are applied to get more accurate results

(a) ***Fuse wire correction*** The gross calorific value calculated above includes the heat liberated by the ignition of Mg fuse wire; hence, this amount of heat has to be subtracted from the total value.

(b) ***Acid Correction*** During combustion, sulphur and nitrogen present in the fuel get oxidized to H_2SO_4 and HNO_3, respectively

$$S + O_2 \rightarrow SO_2$$

$$2SO_2 + O_2 + 2H_2O \rightarrow 2H_2SO_4 \qquad \Delta H = -144000 \text{ cal}$$

$$2N_2 + 5O_2 + 2H_2O \rightarrow 4HNO_3 \qquad \Delta H = -57160 \text{ cal}$$

Hence, the formation of acids is exothermic and this should be subtracted from the obtained value of GCV.

(c) ***Cooling Correction*** Heating and cooling are simultaneous processes. As the temperature rises above the room temperature, the loss of heat occurs due to radiation and the highest temperature recorded will be slightly less than that obtained if there was no heat loss. A temperature correction (cooling correction) is therefore necessary to get the correct rise in temperature.

If the time taken for the water in the calorimeter to cool from maximum temperature attained to room temperature is '*x*' minutes and the rate of cooling is dt / min, then the cooling correction is $x \times dt$ and this is to be added to the rise in temperature.

$$\text{HCV of fuel (H)} = \frac{(W + w)(t_2 - t_1 + \text{cooling correction}) - (\text{Acid + fuse wire correction})}{\text{Mass of the fuel}(x)}$$

Solved examples

1. 0.72 g of a fuel containing 80% carbon, when burnt in a bomb calorimeter, increased the temperature of water from 27.3°C to 29.1°C. If the calorimeter contains 250 g of water and its water equivalent is 150 g, calculate the HCV of the fuel. Give your answer in kJ/Kg.

Solution

Here x = 0.72 g, W = 250 g, w = 150 g, t_1 = 27.3°C, t_2 = 29.1°C

Therefore, HCV of fuel $(\text{H}) = \dfrac{(W+w)(t_2-t_1)}{x}$ cal/g

$\dfrac{(250+150)(29.1-27.3)}{0.72}$ cal/g = 1000 × 4.18 J/g = 4180 J/g = 4180. KJ/Kg

(1 cal = 4.18 Joules).

2. On burning 0.83 g of a solid fuel in a bomb calorimeter, the temperature of 3500 g of water increased from 26.5°C to 29.2°C. Water equivalent of calorimeter and latent heat of steam are 385.0 g and 587.0 cal/g respectively. If the fuel contains 0.7% hydrogen, calculate its gross and net calorific values.

Solution

Here, Weight of fuel (x) =0.83 g; weight of water (W) = 3500 g; water equivalent of calorimeter (w) = 385 g; $(t_2 - t_1)$ = (29.2°C – 26.5°C) = 2.7°C; percentage of hydrogen (H) = 0.7%; Latent heat of steam = 587 cal/g.

HCV of fuel (H) $= \dfrac{(W+w)(t_2-t_1)}{x}$ cal/g $= \dfrac{(3500+385)\times 2.7}{0.83} = 12{,}638$ cal/g

Net calorific value = (HCV – 0.09 H × 587) = (12638 – 0.09 × 0.7 × 587)cal/g.

= (12,638–37) cal/g = 12,601 cal/g

3. A coal sample contains : C = 93%; H = 6% and ash = 1%. The following data were obtained when the above coal was tested in a bomb calorimeter :
   (i) Wt of coal burnt = 0.92 g
   (ii) Wt of water taken = 550 g
   (iii) Water equivalent of bomb and calorimeter = 2200 g
   (iv) Rise in temperature = 2.42°C
   (v) Fuse wire correction = 10.0 cal
   (vi) Acid correction = 50.0 cal

   Calculate the gross calorific value of the coal.

Solution

Wt of coal (x) = 0.92 g; Wt of water taken (W) = 550 g

Water equivalent of bomb and calorimeter (w) = 2200 g

Rise in temperature $(t_2 – t_1)$ = 2.42°C; Fuse wire correction =10.0 cal

Acid correction =50.0 cal; latent heat of condensation of steam = 580 cal/g;

Percentage of hydrogen = 6%

$$\text{GCV} = \frac{(W+w)(t_2-t_1)-(\text{Acid + fuse wire correction})}{x}$$

$$= \frac{(550+2200)\times 2.42\times(50+10)}{0.92} = 7168.5 \text{ cal/g}$$

4. A coal sample contains C = 92%; H = 5% and ash = 3%. When this coal sample was tested in the laboratory for its calorific value in a bomb calorimeter, the following data were obtained

   Wt of coal burnt = 0.95 g

   Wt of water taken = 700 g

   Water equivalent of bomb and calorimeter = 2000 g

   Rise in temperature = 2.48°C

   Fuse wire correction = 10.0 cal

   Acid correction = 60.0 cal

   Cooling correction = 0.02°C

   Calculate the gross and net calorific value of the coal sample in cal/g. Assume the latent heat of condensation of steam as 580 cal/g.

Solution

$$\text{GCV} = \frac{(W+w)(t_2-t_1+\text{cooling correction})-(\text{acid correction + fuse wire correction})}{\text{weight of coal sample taken}}$$

$$= \frac{(2000+700)(2.48+0.02)-(10+60)}{0.95} = \frac{(2700)(2.50)-(70)}{0.95}$$

$$= \frac{6750-70}{0.95} = \frac{6680}{0.95} = 7031.57 \text{ cal/g}$$

LCV or NCV = HCV – 0.09H × 580 cal/g

= 7031.570 – 0.09 × 5 × 580

= 7031.57 – 261 = 6770.57 cal/g

[Ans HCV/GCV = 7031.57 cal/g

LCV/NCV = 6770.57 cal/g]