Week (1)

Combustion

1. Fuel : الوقود

_ Fuel is defined as any matterial which when burnt will produce heat.

Fuels are classified as follows :

1. Solid Fuels : Varions solid fuels used are wood, coal including bituminous coal, anthracite , lignite , peat .

2. Liquid Fuels ; Liquid fuels include petroluum (oil) and its derivatives.

3. Gaseous Fuels : Gaseous fuels consist of natural gas , producer gas , blast furance gas , coal gas. ~~etc~~.

* The aim of this lesson is to identify the students to the fuel as a definition, classification , and the disadvantages and advantages of it.

1.1. Solid Fuels

Natural solid fuels include wood, peat, lignite, bituminous coal and anthracite coal. Wood can be burnt easily and gives maximum intensity of heat very quickly, but is not suitable for boilers, because the calorific value of wood is low (3000 – 4000 kcal/kg).

Coal: The vegetable matter which accumulated under the earth millions of years ago was subjected to the action of pressure and heat. This changed the physical and chemical properties of matter and it got converted into what is call as coal.

× 1.1.

Types of Coal ;

الفحم الرطب

1. Peat: It consists of decayed vegetable matter mainly decomposed water plants and mosses. It has high moisture content and should be dried before burning. Its approximate composition is ;

$C = 60\%$, $H = 5.8\%$, $O = 33\%$, $Ash = 1.2\%$:

Its calorific value is 3500 kcal/kg.

2. Lignite or Brown Coal: It is brown in colour, it burns with a brightly slightly and smoky yellow flame. Its calorific value is 5000 kcal/kg and its approximate composition is $C = 67\%$, $H = 5\%$, $O = 20\%$ and $Ash = 8\%$.

3. Bituminous Coal: It is soft, consists of large amount of volatile matter and is widely used as fuel. It burns with a long yellow and smoky flame. Its calorific value is 7800 kcal/kg and approximate composition is:

$C = 83.5\%$, $H = 5\%$, $O = 5\%$, $Ash = 6.5\%$.

4. Anthracite Coal: It is black in colour and burns with a short bluish flame and the amount of ash produced due to its burning is very little. Its calorific value is 8500 kcal/kg and approximate composition is as follows:

$C = 90\%$, $O = 2\%$, $H = 3\%$ and $Ash = 5\%$ 3

((proceed it))

1.2. Liquid Fuels

Liquid fuels include petroleum and its derivatives. Fractional distillation of crude petroleum helps in separating it into its various varieties such as gasoline, kerosene, oil gas, light diesel fuels and residual oil.

- Advantages of liquid fuels over solid fuels;

1. Handling of liquid fuels is easy and they require less storage space.

2. Liquid fuels can be fired easily, and the maximum temperature is attained in lesser time as compared to solid fuels.

3. The solid fuels leave a large quantity of ash after burning and the disposal of ash becomes a problem. Whereas the liquid fuels leave very little ash after burning.

4. The combustion of liquid fuels is uniform.

5. The combustion of liquid fuels can be easily controlled.

The disadvantages of liquid fuels are as follows:

1. They are costly as compared to solid fuels.

2. They require special type of burners for their burning.

3. Sometimes they give unpleasant odours.

4. There is danger of explosions,

5. In cold climates the oil stored in tanks is to be heated in order to avoid stoppage of oil flow.

1.3. Gaseous Fuels

The gaseous fuels can be classified as follows:

(i) Natural - Natural gas.

(ii) Prepared - Coal gas, blast furance gas, producer gas, ~~and water gas.~~

(a) Natural Gas: Natural gas comes out of gas wells and petroleum wells. It is mainly composed of methane (CH_4) = 85%, ethane (C_2H_6) = 10% and other hydrocarbons = 5%. It is colourless and non poisonous. The calorific value of natural gas is 525 kcal/m³.

(b) Blast Furance Gas: This gas is obtained as a by-product from blast furance used for producing pig iron. Its approximate composition is $CO = 30\%$, $N_2 = 52\%$, $H_2 = 3\%$, $CO_2 = 2\%$, and $CH_4 = 3\%$.

The calorific value of this gas is 970 kcal/m³.

(c) Coal Gas: Coal gas is a by-product gas obtained during the destructive distillation of coal. Its calorific value is 7600 kcal/m^3. Its approximate composition is $CH_4 = 35\%$, $H = 45\%$, $CO = 8\%$, $N = 6\%$, $CO_2 = 2\%$ and other hydrocarbons = 4%.

(d) Producer Gas: Producer gas is produced during incomplete combustion of coke in current of air. Its main constituents are nitrogen and carbon monoxide. Its approximate composition is $N = 62\%$, $CO = 23\%$, $H_2 = 6\%$, $CO_2 = 5\%$, $CH_4 = 4\%$. Its calorific value is 1200 kcal/m^3.

(e) Water Gas: Water gas is obtained by passing a blast of steam through a deep bed of red hot coke. Its main constituents are CO_2, CO and H_2.

- Advantages of Gaseous Fuels over Solid Fuels:

1. It is easy to control the length and nature of flame and hence temperature control is easier.

2. Gaseous fuels do not contain ash and other foreign matter and burn completely. Their use is economical as compared to solid and liquid fuels. No ash removal is required.

3. Handling of gaseous fuel is not required as they can be easily piped into the furance.

4. Lesser amount of excess air is needed to burn them completely.

5. Greater cleanliness is assured as the soot and smoke is practically nil.

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Calorific Value of Fuel (Heating Value):

The calorific value of fuel is defined as the amount of heat produced when unit quantity (one kilogram of solid or liquid fuel or one cubic metre of gaseous fuel) of fuel is completely burnt under standard conditions.

The calorific value is expressed as kcal per kg or kcal per cubic metre of gaseous fuel. The calorific value of a fuel can be classified in two ways:

ⓘ Higher calorific value (H. C.V.)

ⓘⓘ Lower calorific value (L. C. V.)

The higher or gross of calorific value is the total amount of heat produced when unit quantity of fuel is burnt completely and the products of combustion have been cooled to room temperature, generally taken as 15°C.

The lower calorific value is the net amount of heat produced when unit quantity of fuel is completely burnt and the products of combustion are not cooled to room temperature but are allowed to escape.

According to Dulong formula the calorific value of a fuel is given by the following relation:

$$H.C.V. = \frac{1}{100}\left[8080C + 34500\left[H - \frac{O}{8}\right] + 2220S\right] \text{kcal/kg.}$$

where C. H. O. and S. represent the percentage by weight of carbon, hydrogen, oxygen and sulphur respectively.

The net or lower calorific value (L.C.V.) is obtained by subtracting from H.C.V. the heat carried by the products of combustion especially by steam which can be taken as 588.76 kcal/kg of water vapours formed due to burning of 1 kg of fuel.

$$\therefore L.C.V._{@15^\circ C} = (H.C.V. - 588.76 * W)\ kcal/kg.$$

where W is the amount of water vapours formed by the combustion of 1 kg of fuel.

where, $W = (m + 9H_2)$ kg
$m =$ mass of moisture / kg of fuel,
$H_2 =$ mass of H_2 / kg of fuel.

The specific enthalpy of evaporation per kg of steam which leaves with the combustion products is taken as 2442.0 kJ/kg of steam at 25°C. From this then,

$$L.C.V._{@25^\circ} = \{H.C.V._{@25^\circ C} - 2442(m + 9H_2)\},\ kJ/kg\ of\ fuel$$

Example: The percentage composition by the weight of a sample of coal is given as below:

$C = 65.5\%$; $H_2 = 6.65\%$; $O_2 = 17.5\%$

$S = 1.8\%$.

Using Dulong's formula, calculate the calorific values of coal.

Solution:

According to Dulong's formula, the higher calorific value (H.C.V.) is given by the following relation;

$$H.C.V. = \frac{1}{100}\left[8080C + 34500\left[H - \frac{O}{8}\right] + 2220S\right] \text{ kcal/kg}$$

$$H.H.V. = \frac{1}{100}\left[8080 * 65.5 + 34500\left(6.65 - \frac{17.5}{8}\right) + 2220 * 1.80\right]$$

$$= \frac{1}{100}\left(529240 + 153956 + 3996\right) = 6871.92 \text{ kcal/kg}$$

Steam produced $= 0.0665 \times 9 = 0.5985$ kg of steam/kg of fuel

∴ Lower calorific value (L.C.V.) = H.C.V. − 588.76*W

L.C.V. = 6871.92 − 588.76 * 0.5985 =

= 6871.92 − 352.37 = 6519.55 kcal/kg

3'rd week lecture

Combustion of Fuels

The combustion of fuels is defined as a chemical combination of oxygen in the atmospheric air and hydro - carbons. It is usually expressed both
ⓘ qualitively and
ⓘⓘ quantitatively, by equations known as chemical equations which indicate the nature of chemical reaction taking place.

Adequate supply of oxygen is very essential for the complete combustion of a fuel in order to obtain maximum amount of heat from a fuel.

Combustion of fuels is accomplished by mixing fuel and air at elevated temperature. The combustion process is simply expressed as follows:

Fuel + Air = Products of combustion + Heat Liberated.

The oxygen contained in the air unites chemically with carbon, hydrogen and other elements in fuel to produce heat. The amount of heat liberated during the combustion process depends on the amount of oxidation of the constituents of fuel and the nature of fuel (chemical composition of fuel).

In order that the combustion of fuel may take place with high efficiency, the following conditions must be fulfilled:

1. The amount of air supplied should be such that it is sufficient to burn the fuel completely. Complete combustion of fuel means complete oxidation of all the combustible material in the fuel. A deficiency of air causes incomplete combustion of fuel which results in considerable unburnt fuel being discharged from the furnace, whereas too much supply of air simply dilutes the gases and cools the furnace.

2. The air and fuel should be thoroughly mixed so that each combustible particle comes in intimate contact with the oxygen contained in the air.

3. The fuel should remain in the furance for sufficient time till it get burnt completely.

4. The temperature in the furance should be high enough to ignite the incoming air fuel mixture.

Products of Combustion

The complete combustion of fuel produces various gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2), water vapour nitrogen (N_2) and oxygen (O_2). Nitrogen comes from air supply and oxygen from excess air.

Water vapour is produced from the following three sources:

ⓘ Moisture originally contained in the coal.
ⓘⓘ Vapour produced by combustion of hydrogen.
ⓘⓘⓘ The water vapour of atmospheric humidity.

If all the carbon present in the fuel does not get burn completely then carbon monoxide (CO) is also produced. The flue gases will have considerable amount of carbon monoxide in them if the oxygen supply is less. While large excess of air would mean that a large amount of sensible heat would be lost in flue gases.

Combustion Chemistry

The combustion process involves chemical reactions. The combustible elements in fuels consists of carbon, hydrogen and sulphur.

The chemical equations represent the combustion of C, H_2, S, CH_4, etc., are described as follows:

(i) Combustion of Carbon

$$C + O_2 \longrightarrow CO_2$$

Substituting the values of molecular weight in equation,

$$12 + 2 \times 16 \longrightarrow 12 + 16 \times 2$$

$$12 + 32 = 12 + 32$$

$$1 + \frac{8}{3} = 1 + \frac{8}{3}$$

$$1 + \frac{8}{3} = \frac{11}{3}$$

This means that 1 kg of carbon requires 8/3 kg of oxygen for its complete combustion and produces 11/3 kg of carbon dioxide.

If the amount of oxygen supplied is not sufficient the combustion of carbon is incomplete and the product of combustion will be carbon monoxide.

$$2C + O_2 \rightarrow 2CO$$

$$2 \times 12 + 16 \times 2 = 2(12+16)$$

$$24 + 32 = 56$$

$$1 + \frac{4}{3} = \frac{7}{3}$$

which means that 1 kg of carbon needs 4/3 kg of oxygen to produce 7/3 kg of carbon monoxide. Further burning of CO produces CO_2.

$$2(12+16) + 16 \times 2 = 2(12+32)$$

$$56 + 32 = 88$$

$$1 + \frac{4}{7} \rightarrow \frac{11}{7}$$

This means that 1 kg of CO needs 4/7 kg of oxygen and produces 11/7 kg of CO_2.

(ii) Combustion of Hydrogen:

Burning of hydrogen with oxygen produces water vapors,

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$2(1+1) + 16\times2 \rightarrow 2(2+16)$$

$$4 + 32 \rightarrow 36$$

$$1 + 8 \rightarrow 9$$

This means that 1 kg of hydrogen combines with 8 kg of oxygen to produce 9 kg of water.

(iii) Combustion of Sulphur; When sulphur burns with oxygen it produces sulphur dioxide.

$$S + O_2 \rightarrow SO_2$$

$$32 + 16\times2 \rightarrow 32 + 16\times2$$

$$32 + 32 \rightarrow 32 + 32 \rightarrow 64$$

or, 1 kg of sulphur + 1 kg of oxygen → 2 kg of sulphur dioxide.

Table (1)

Substance (1 kg)	Oxygen Required (in kg)	Products of Combustion (in, kg)			
		CO	CO_2	H_2O	SO_2
C	8/3	—	11/3	—	—
CO	4/7	—	11/7	—	—
H_2	8	—	—	9	—
S	1	—	—	—	2

Combustion of Gaseous Fuels

Gaseous fuels are usually measured by volume (in cubic meters). The chemical equations are described as follows:

(i) Combustion of Hydrogen :

$$2H_2 + O_2 \rightarrow 2H_2O$$

2 vol. + 1 vol. → 2 vol.

1 cu-meter + $\frac{1}{2}$ cu-meter → 1 cu-metre. This means that one cu-meter of hydrogen requires $\frac{1}{2}$ cu-meter of oxygen to produce one cu-meter of water.

(ii) Combustion of Methane : When methane burns with oxygen it gives carbon dioxide and water.

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

1 vol. + 2 vol. → 2 vol. + 1 vol.

1 cu-meter + 2 cu-meter → 2 cu-meter + 1 cu-meter.

Thus 1 cu-meter of methane needs 2 cu-metter of oxygen for combustion and produces 2 cu-meter of water and 1 cu-meter of carbon dioxide.

(iii) Combustion of CO: When carbon monoxide burns in oxygen, it gives CO_2.

$$2CO + O_2 \longrightarrow 2CO_2$$

$$2\text{ vol.} + 1\text{ vol.} \longrightarrow 2\text{ vol.}$$

$$1\text{ cu-meter} + \frac{1}{2}\text{ cu-meter} \longrightarrow 1\text{ cu-meter } (m^3).$$

Thus 1 m^3 of carbon monoxide needs one-half in m^3 of oxygen to produce one cubic meter of carbon dioxide.

(iv) Combustion of Ethylene (C_2H_4): When C_2H_4 burns in oxygen it gives CO_2 and H_2O.

$$C_2H_4 + 3O_2 \longrightarrow 2CO_2 + 2H_2O$$

$$1\text{ vol.} + 3\text{ vol.} \longrightarrow 2\text{ vol.} + 2\text{ vol.}$$

or, $1m^3 + 3m^3 \longrightarrow 2m^3 + 2m^3$

Thus 1 m^3 of ethylene combines with 3 m^3 of oxygen to produce 2 m^3 of CO_2 and 2 m^3 of water vapours.

4th week lecture

Coal Selection

While selecting coal for steam power plants the following properties should be considered:

1. Size and Grade: The size and grade of coal will determine the type of equipment to be used for the burning the coal.

2. Heating Value: The coal selected should have high heating value (calorific value).

3. Contents of moisture, volatile matter, fixed carbon, ash and sulphur. The slagging characteristics depend on ash temperature and corrosion characteristic depend on sulphur contents.

4. Coking and caking tendency of coal that is retention of original shape during combustion vs. softening.

5. Physical properties such as resistance to degradation and size consistency.

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6. Various constituents indicated by approximate the ultimate analysis.

7. Grindability : the ease with which a coal can be pulverised.

_Ranking and Grading of Coal :

According to ASME there are two methods of ranking of coal ;

ⓘ Higher ranking of coal is done on the basis of fixed carbon percentage (dry basis).
ⓘⓘ Lower ranking is done on the heating value on the moist basis.

For example a coal having 6% C and a calorific value of 5000 kcal/kg is ranked as (60-500) rank.

Grading of coal is done on the following basis:
i_ Size ;
ii_ Heating value ;
iii_ Ash content ;
iv_ Ash softening temperature ;
v_ Sulphur content.

For example, a coal of grade written as 6-10 cm, 500-A8-F24 S 1.7 means;

a- coal has a size of 6-10 cm
b- coal heating value is 5000 kcal/kg
c- coal has ash content 8 to 10%
d- ash softening temp. is 2400°F
e- sulphur content of coal is 1.7%.

-Methods of Analysis the Composition of Solid Fuels:

The various constituents of solid fuels are carbon, hydrogen, oxygen, sulphur, nitrogen and mineral matter.

The following methods of analysis are used to determine the composition of coal:

1. Ultimate analysis,
2. Proximate analysis.

1. Ultimate Analysis: The analysis is used to express in percentage by weight of carbon, hydrogen, nitrogen, sulphur, oxygen and ash and their sum is taken as 100%. Moisture is expressed separately. This analysis enables to find the amount of air required for the combustion of 1 kg of coal and to calculate the heating value of coal.

The ultimate analysis of most of the coals indicates the following ranges of various constituents.

Cons. :	C	H_2	O_2	S	N_2	Ash
Perc. :	50-90%	2-5.5%	2-40%	0.5-3%	0.5-7%	2-30%

2. Proximate Analysis

This analysis is used to determine the following components:

i- Moisture.
ii- Volatile matter (carbon combined with hydrogen and other gases that are driven off on heating).
iii- Ash
iv- Fixed carbon.

They are expressed in percentage by weight and their sum is taken as 100%.

- Ash: Is the combustion product of mineral matters presents in the coal. It comprises mainly of silica (SiO_2), alumina (Al_2O_3) and other oxides such as CaO and MgO.

A coal with high ash content has following properties: ① is harder and stronger.
② has lower calorific value.
③ produces more slag (impurities) in the blast furnace.

- Weight of Excess Air Supplied

The weight of excess air supplied or required during combustion of coal is calculated from the weight of unused oxygen in flue gases after CO is present in flue gases is burnt to CO_2.

Assume, W_1 = weight of flue gases per kg of Fuel,
W_2 = percentage weight of oxygen present in flue gases,

W_3 = percentage weight of CO present in flue gases

As 1 kg of CO need 4/7 kg of oxygen to burn to CO_2.
∴ Oxygen required to burn W_3 kg of CO to CO_2 is,

$$W_4 = \frac{W_3}{100} \times \frac{4}{7}$$

∴ Excess Oxygen, $W_5 = \frac{W_2}{100} - W_4$

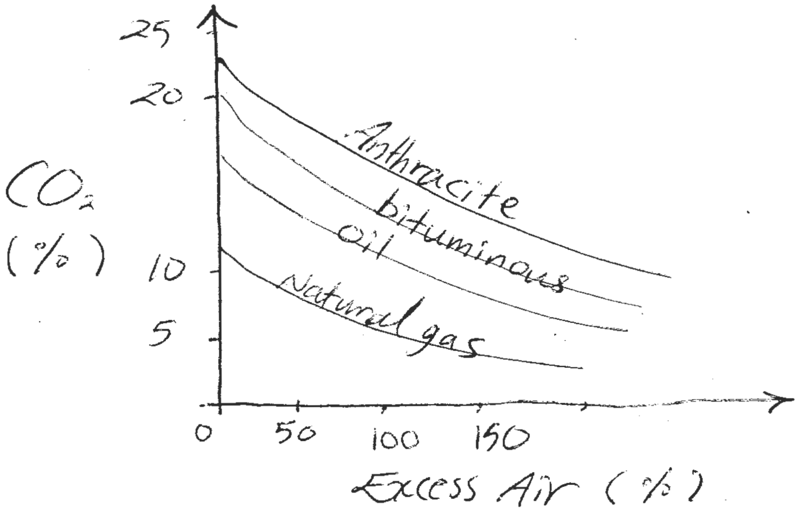
Weight of excess oxygen per kg of fuel (W_6)
= Weight of excess oxygen per kg of flue gases
× Weight of flue gases per kg of fuel

$$\therefore, \quad W_6 = W_5 \times W_1$$

Therefore, the weight of excess air supplied is,

$$= W_6 * \frac{100}{23}$$

The amount of CO_2 in flue gases depends on type of fuel and excess air supplied to the furnace. The following figure shows typical variation of CO_2 in flue gases and excess air (percent by volume) for complete combustion of various types of fuels.



5th Week Lecture

_The total amount of air needed for complete combustion of a fuel depends on the following factors:

1- Type of Fuel.
2- Furance arrangement.
3- Heat transfer surface arrangement.

_Requirement of Fuel

A fuel should possess the following requirements:

1- Calorific value: The fuel selected should have high calorific value.
2- Price: It should be cheap.
3- Operating efficiency: The fuel should burn more effectively. It should produce minimum amount of dust, smoke, slagging.
4- Refuge disposal: The fuel should produce minimum ash on burning.
5- Handling cost: The handling cost should be minimum. Handling cost of coal at power station is maximum and gas requires minimum handling cost whereas handling cost of oil is intermediate.
6- Operating labour cost: The operating labour cost is maximum in coal fired plants whereas it is minimum where gas is used as fuel.

6- Operating labour cost: The operating labour cost is maximum in coal fired plants whereas it is minimum where gas is used as fuel.

- Principal Stages of Combustion:

The combustion of fuel is a complicated physical and chemical process in which the combustible elements of the fuel combine with the oxygen of air with the evolution of heat attended by a sharp rise in temperature and formation of flame. During the burning of any fuel two stages are observed:

i - Ignition.
ii - Combustion.

Ignition is the period during which the fuel is gradually raised in temperature. On attaining a definite temperature the fuel is ignited and stable combustion sets in. When solid fuel is introduced into the furnace, moisture is first removed and the volatiles begin to be liberated. The resultant gaseous products of the fuel decomposition are gradually heated to the ignition point and burn in a flame over the solid part of the fuel.

Combustion of the gaseous substances, heats the coke which begins to burn stably when the ignition points is reached. At this stage maximum temperature is generated.

Burning down is the final stage in the combustion of solid fuel. Gasification and the combustion of solid elements are completed in this stage and enough heat is generated to maintain combustion at a sufficiently high temperature.

Complete Combustion

It is process in which the combustible elements of fuel combine chemically with the oxygen of air at a definite temperature.

The flue gases produced consists of CO_2, SO_2, water vapour (H_2O), oxygen (O_2) and nitrogen (N_2).

Incomplete Combustion;

A deficiency in air supplied causes incomplete combustion of fuel which results in considerable unburnt fuel being discharged from the furance. The presence of carbon monoxide gas (CO) in the combustion products indicates incomplete combustion, where the combustion is accompanied by soot formation.

Weight of Carbon in flue gases:

The weight of carbon contained in 1 kg of flue gases can be calculated from the amounts of CO_2 and CO present in it, as follows:

W_c = weight of carbon in 1 kg of flue gases

$$= \frac{3}{11} CO_2 + \frac{3}{7} CO.$$

where, CO_2 and CO are the percentage weight of carbon dioxide and carbon monoxide per kg of flue gas, respectively.

- Weight of flue gas per kg of fuel burnt;

The actual weight of dry flue gases can be obtained by comparing the weight of carbon present in flue gases with the weight of carbon in the fuel.

Assume, $W_{c_{fuel}}$ = weight of carbon in 1kg of fuel.

W = Weight of flue gas per kg of fuel burnt.

$= W_{cfuel} / W_c$

where, W_c = weight of carbon in 1kg of flue gases.

Temperature of Fuel Combustion:

The combustion of fuel is always accompanied by heat losses. Therefore, the real temperature or actual temperature of combustion is lower than the theoretical temperature of combustion which is obtained in ideal cases without heat losses. The following table shows the theoretical temperature of combustion for various fuels in °C.

Type of fuel	Excess Air Coefficient			
	1.0	1.3	1.5	2.0
	Temperature of Combustion in °C			
Anthracite	2270	1845	1665	1300
Lignite	1875	1590	1425	1150
Peat	1700	1510	1370	1110
Fuel Oil	2125	1740	1580	1265
Gas	2000	1749	1478	1167

Ex; The percentage composition of a sample of coal was found to be as follows:

$C = 85\%$; $H_2 = 3\%$; $O_2 = 2\%$; Ash = 10%.

Determine the minimum weight of air required for the complete combustion of one kg of coal.

Solution:

$C = 0.85$ kg / kg of fuel

$O_2 = \frac{8}{3}$ kg required per 1 kg of carbon

$\therefore$ Oxygen per kg of fuel @ C $= 0.85 \times \frac{8}{3} = 2.266 \frac{\text{kg of } O_2}{\text{kg of Coal}}$

$H_2 = 0.03$ kg / kg of fuel

$O_2 = 8$ kg required per 1 kg of H_2

$\therefore O_2$ per kg of fuel @ H_2 $= 0.03 \times 8 = 0.24 \frac{\text{kg of } O_2}{\text{kg of Coal}}$

$\therefore$ Total oxygen required $= 2.266 + 0.24 - 0.02$
$= 2.486$ kg of O_2/kg of fuel.

Weight of air required for complete combustion of 1 kg of fuel $= 2.486 \times \frac{100}{23} = 10.8$ kg.

Ex: The percentage composition by weight of a sample of coal; was found to be as follows:
$C = 24\%$; $H_2 = 5\%$; $O_2 = 8\%$; Ash $= 63\%$

It was also observed that dry flue gas had the following composition by volume;
$CO_2 = 10\%$; $CO = 2\%$; $O_2 = 13\%$; $N_2 = 75\%$.

Determine the following:
a- Minimum weight of air required for complete combustion of 1 kg of coal.
b- Weight of excess air required per kg of coal.

Solution;- (a)
$C = 0.24$ per kg of coal
$O_2 = 8/3$ per kg of substance of C.
O_2 required per kg of coal @ C $= 0.24 \times \frac{8}{3}$
$= 0.64$ kg

$H_2 = 0.05$ per kg of coal
$O_2 = 8$ kg per kg of H_2
O_2 required per kg of coal @ $H_2 = 0.4$ kg

Total oxygen required $= 0.64 + 0.4 - 0.08 = \boxed{0.96 \text{ kg.}}$

∴ Minimum weight of air required per kg of coal $= 0.96 \times \frac{100}{23}$

$$= \boxed{4.17 \text{ kg.}}$$

(b)

- $CO_2 = 0.1$ m³/m³ of flue gas

$M_{CO_2} = 44$ kg/m³

$\overline{W}_{CO_2} = 4.4$ kg

- $CO = 0.02$ m³/m³ of flue gas

$M_{CO} = 28$ kg/m³

$\overline{W}_{CO} = 0.56$ kg

- $O_2 = 0.13$ m³/m³ of flue gas

$M_{O_2} = 32$ kg/m³

$\overline{W}_{O_2} = 4.16$ kg

- $N_2 = 0.75$ m³/m³ of flue gas

$M_{N_2} = 28$ kg/m³

$\overline{W}_{N_2} = 21$ kg/m³ of fluegases

$$\overline{W}_T = W_{CO_2} + W_{CO} + W_{O_2} + W_{N_2}$$

$$= 4.4 + 0.56 + 4.16 + 21 = 30.12 \text{ kg flue/m}^3 \text{ flue}$$

- $W_{CO_2} = \overline{W}_{CO_2} / \overline{W}_T = 0.146$ kg/kg of fluegas

- $W_{CO} = \overline{W}_{CO} / \overline{W}_T = 0.018$ kg/kg of flue gas.

- $W_{O_2} = \overline{W}_{O_2} / \overline{W}_T = 0.14$ kg / kg of flue gas.
- $W_{N_2} = \overline{W}_{N_2} / \overline{W}_T = 0.696$ kg / kg of flue gas.

Weight of carbon per kg of coal = 0.24 kg / kg of coal.

Weight of carbon per kg of the flue gas

= Weight of carbon in 0.146 kg of CO_2
+ Weight of carbon in 0.018 kg of CO

$$= \frac{3}{11} \times 0.146 + \frac{3}{7} \times 0.018$$

= 0.048 kg / kg of flue

$\therefore$ Weight of flue gas per kg of coal $= \frac{0.24}{0.048} = 5$ kg flue / kg of fuel

Weight of excess oxygen per kg of flue gas
= Amount of oxygen in flue gas − Oxygen required to burn CO.

$$= 0.14 - \frac{4}{7} \times 0.018 = 0.13 \text{ kg / kg of flue}$$

$\therefore$ Weight of excess oxygen / kg of coal = $5 \times 0.13 = 0.65$ kg/kg of fuel
$\therefore$ Weight of excess air / kg of coal $= 0.65 \times \frac{100}{23} = 2.83$ kg.

6th week Lecture

Ex: Calculate the amount of air required to burn one kg of fuel and product of combustion for a fuel the percentage composition of which is given as follows:

$$C = 80\% \; ; \; H_2 = 20\%$$

Solution:-

Substance	Weight per kg of fuel	O_2 reqd. per kg of substance	O_2 reqd. per kg of fuel
C	0.8	8/3	$0.8 \times 8/3 = 2.13$
H_2	0.2	8	$0.2 \times 8 = 1.6$

Total oxygen required = 2.13 + 1.6 = 3.73 kg.

$\therefore$ Weight of air required $= 3.73 \times \frac{100}{23} = 16.2$ kg

Products of Combustion

$$C + O_2 \rightarrow CO_2 \Rightarrow 12 + 32 \rightarrow 44$$

$\Rightarrow \therefore 1$ kg of C $+ \frac{8}{3}$ kg of $O_2 \rightarrow \frac{11}{3}$ kg of CO_2

$\therefore \frac{8}{3}$ kg of O_2 gives $CO_2 = \frac{11}{3}$ kg of CO_2/kg of C

2.13 kg of O_2 gives $CO_2 = \frac{11}{3} \times \frac{3}{8} \times 2.13 \; \frac{\text{kg of } CO_2}{\text{kg of fuel}}$

$\therefore CO_2 = 2.93$ kg /kg of fuel

Similarly, $2H_2 + O_2 \longrightarrow 2H_2O$

$\therefore$ 1 kg of H_2 + 8 kg of $O_2 \longrightarrow$ 9 kg of H_2O

$$H_2O = 9 \times \frac{1}{8} \times 1.6 = 1.8\ \overset{H_2O}{kg}/kg \text{ of fuel.}$$

Ex: A gas used as fuel has the following composition by volume;

$H_2 = 27\%$; $CO_2 = 18\%$; $CO = 12.5\%$; $CH_4 = 2.5\%$

$N_2 = 40\%$

Calculate the volume of air required for complete combustion of one cubic-metre of the gas.

Sol.:-

Name of gas	Vol. per cu. meter of fuel	O_2 reqd. per m^3 of constituent	O_2 reqd. per m^3 of fuel
H_2	0.27	1/2	0.135
CO_2	0.18	—	—
CO	0.125	1/2	0.062
CH_4	0.025	2	0.05
N_2	0.4	—	—

Total oxygen reqd = 0.135 + 0.062 + 0.05 = 0.247 m^3/m^3 of fuel

$\therefore$ volume of air = $0.247 \times \frac{100}{21}$ = 1.176 m^3 of air/m^3 of fuel

Ex: The percentage composition of a sample of coal is found to be as follows: $C = 88\%$; $H_2 = 4.3\%$; $O_2 = 3\%$; $N_2 = 0.7\%$; $S = 1\%$; Ash = 2 %.

(a) Calculate the minimum weight of air required for complete combustion of one kg of this coal,

(b) If 40% excess air is supplied, calculate the percentage composition by volume of the dry flue gases.

Solution:

Substance	Weight/kg of coal (kg)	Weight of oxygen/kg of substance (kg)	Weight of oxygen reqd. (kg)	Weight of combustion products		
				CO_2	SO_2	N_2
C	0.88	8/3	2.35	3.23	—	—
O_2	0.04	—	-0.04	—	—	—
H_2	0.043	8	0.344	—	—	—
N_2	0.007	—	—	—	—	0.007
S	0.01	1	0.01	—	0.02	—
Ash	0.02	—	—	—	—	—

$$\text{Total oxygen required} = 2.35 + 0.344 + 0.01 - 0.04$$
$$= 2.664\ \text{kg}$$

$$\therefore \text{Minimum amount of air required} = 2.664\ \text{kg} \times \frac{100}{23}$$
$$= \underline{\underline{11.58\ \text{kg}}}$$

(b) As 40% excess air is supplied;

$\therefore$ N_2 in actual air supply $= 11.58 \times 0.77 \times 1.4$
$= 12.5$ kg

$\therefore$ Total nitrogen $= 12.5 + 0.007 = 12.507$ kg

Excess oxygen $= 11.58 \times \frac{23}{100} \times 0.4 = 1.065$ kg.

Substance	Weight per kg of coal	Molecular Weight	Parts by volume m^3	Percentage vol. %
CO_2	3.23	44	3.23/44 = 0.073	13.13%
SO_2	0.02	64	0.0003	0.054%
O_2	1.065	32	0.0333	6%
N_2	12.507	28	0.45	80.85%
		Total	0.557	

13-11-2011, Sunday

– Stoichiometric, or chemically correct, air/fuel ratio:

A stoichiometric mixture of air and fuel is one that contains just sufficient oxygen for the complete combustion of the fuel. A mixture which has an excess of air is termed a weak mixture, and one which has a deficiency of air is termed a rich mixture. The percentage of excess air is given by the following,

Percentage excess air

$$PEA = \frac{\text{Actual A/F ratio} - \text{Stoichiometric A/F ratio}}{\text{Staichiometric A/F ratio}} \quad \text{---(PEA)}$$

(where A denotes air and F denotes fuel).

For gaseous fuels the ratios are expressed by volume and for solid and liquid fuels the ratios are expressed by mass. The eq. (PEA) gives a positive result when the mixture is weak, and a negative result when the mixture is rich. For boiler plant the mixture is usually greater than 20% weak; for gas turbines it can be as much as 300% weak, petrol engines have to meet various conditions of load and speed, and operate over a wide range of mixture strengths.

The following definition is used,

$$\text{Mixture Strength} = \frac{\text{Stoichiometric A/F ratio}}{\text{Actual A/F ratio}}$$

The working values range between 80% (weak) and (120% (rich).

Where fuels contain some oxygen this oxygen is available for the combustion process, and so the fuel requires a smaller supply of air.

Exhaust and flue gas analysis;

The products of combustion are mainly gaseous, when a sample is taken for analysis it is usually cooled down to a temperature which is below the saturation temperature of the steam present. The steam content is therefore not included in the analysis, which is then quoted as the analysis of the dry products. Since the products are gaseous, it is usual to quote the analysis by volume. An analysis which includes the steam in the exhaust is called a wet analysis.

Ex: Calculate the stoichiometric A/F ratio for the combustion of a sample of dry anthracite of the following composition by mass:

C 90%; H_2 3%; O_2 2.5%; N_2 1%; S 0.5%; Ash 3%.

Determine the A/F ratio and the dry and wet analysis of combustion products by volume, when 20% excess air is supplied.

Solution:—

Const.	Mass / kg coal	kg O_2 req. / kg coal	Products / kg Coal
C	0.9	$0.9 \times \frac{8}{3} = 2.4$	$0.9 \times \frac{11}{3} = 3.3$ kg CO_2
H_2	0.03	$0.03 \times 8 = 0.24$	$0.03 \times 9 = 0.27$ kg H_2O
O_2	0.025	-0.025	----------
N_2	0.01	---	0.01
S	0.005	$0.005 \times 1 = 0.005$	$0.005 \times 2 = 0.01$ kg SO_2
Ash	0.03	---	

Total $O_2 = 2.62$ kg

From table:

O_2 req. per kg of coal = 2.62 kg

∴ Air req. per kg of coal = 2.62/0.23
= 11.39 kg A / kg F

N_2 associated with this air = 0.77 × 11.39
= 8.77 kg N_2.

Then, total N_2 in products $= 8.77 + 0.01 = 8.78$ kg.

The stoichiometric A/F ratio $= 11.39/1$

For an air supply which is 20% in excess, using equation (P.E.A),

Actual A/F ratio $= 11.39 + 0.2 * 11.39 = 1.2 * 11.39$
$= 13.67/1$

Therefore, N_2 supplied $= 0.77 * 13.67 = 10.53$ kg.

Also, O_2 supplied $= 0.23 * 13.67 = 3.14$ kg.

In the products then, it is obtained

$N_2 = 10.53 + 0.01 = 10.54$ kg.

and;

excess $O_2 = 3.14 - 2.62 = 0.52$ kg

Products	Mass/kg coal	% mass	Mw	Moles/kg coal	% Vol. wet	% Vol. dry
CO_2	3.3	22.5	44	0.075	16.07	16.61
H_2O	0.27	1.84	18	0.015	3.21	—
SO_2	0.01	.007	64	0.00016	0.03	0.035
O_2	0.52	3.6	32	0.0163	3.5	3.61
N_2	10.54	72	28	0.3764	80.67	83.35
	$\Sigma = 14.64$ kg					

Total wet $= 0.4666$

$(-H_2O) = 0.015$

Total dry $= 0.4516$

The Universal Gas Constant:

Consider two gases A and B both with the same pressure P, volume V, and temperature T. Let their masses be m_A and m_B, respectively.

By the characteristic equation of a perfect gas,

$$\frac{PV}{T} = m_A R_A = m_B R_B \quad \text{-----} \; ①$$

where R = Characteristic gas constant.

Let the relative molecular masses of the gases be M_A and M_B, respectively.

By Avogadro's Hypothesis, the masses of equal volumes of different ~~gases~~ at the same pressure and temperature are proportional to their relative molecular masses. Hence, it follows from eq. ① that since,

$$m_A R_A = m_B R_B$$

then,

$$M_A R_A = M_B R_B \quad \text{-----} \; ②$$

From this, then, it appears that the product of relative molecular mass and characteristic gas constant of all gases is always a constant.

This constant is called the universal or molar gas constant, R_m.

Hence,

$$MR = R_m$$

For air, average values of
$R = 0.287$ kJ/kg·K, and $M = 28.95$ kg.

which is 1 mole of air (i.e per kgmole)

$$\therefore R_M = 0.287 * 28.95 = \underline{8.313 \text{ kJ/kgmole} \cdot K}$$

The mole (symbol the 'mol')

· A mole of a substance is defined as the mass of the substance equal to its relative molecular mass.

If the unit of mass is taken as the kilogramme, then,

1 mole O_2 = 32 kg O_2 ; 1 mole C = 12 kg C

1 mole H_2 = 2 kg H_2 ; 1 mole S = 32 kg S

1 mole CO_2 = 44 kg CO_2 .

Since the kilogramme had been used, the mole is referred to as the 'kilogramme mole', written kg mol, and in the case of O_2, it would have been 32 kilogramme of O_2.

To determine the number of moles of gas for example it is necessary to divide the mass of gas by its relative molecular mass. Thus,

$$n = m/M \quad \text{---} ①$$

where, n = number of moles,

m = mass of gas,

M = relative molecular mass of gas.

From this,

$$m = nM \quad \text{----} ②$$

Also, since $M \cdot R = R_M$

then, $R = R_M/M$ ---- ③

From the Characteristic Equation of a Perfect Gas,

$$PV = mRT \quad \text{----} ④$$

Substituting equations ② and ③ into ④,

$$PV = nM\frac{R_M}{M}T$$

or,

$$PV = nR_MT \quad \text{-----} ⑤$$

Volume of one mole of gas :

Since $PV = nR_MT$

then ,

$$V = \frac{nR_MT}{P}$$

which, for 1 mole of gas, becomes,

$$V = \frac{R_MT}{P} \text{ since } n=1$$

This equation is independent of any particular gas, and it shows that the volume of one mole of any gas at the same pressure and temperature is constant.

Thus, for any gas at a pressure of 101.325 kPa and a temperature of 0°C, the volume of one kg·mol is,

$$V = \frac{8.3143 \times 273.15}{101.325} = \underline{22.4\,m^3}$$

– Average relative molecular mass of a gas mixture:

$$\text{Number of moles of gas} = \frac{\text{Mass of gas}}{\text{Relative molecular mass of gas}},$$

or, $$n = \frac{m}{M} \quad \text{---} ①$$

From this,

$$\text{Relative Molecular mass of gas} = \frac{\text{Mass of gas}}{\text{Number of moles of gas}}, \text{ or}$$

$$M = \frac{m}{n} \quad \text{---} ②$$

For a gas mixture, this equation ② can be used to determine the average relative molecular mass of a gas mixture.

The mass of a gas mixture is made up of the masses of the individual amounts of gas present.

where, $m = nM$ — ③

Thus the mass of a gas mixture,

$$m_g = n_1 M_1 + n_2 M_2 + n_3 M_3 + \text{---} \quad ④$$

where 1, 2, 3, etc., represent the different gases in the mixture.

Also, the number of moles of gas mixture

$$n_g = n_1 + n_2 + n_3 + --- \quad —— ⑤$$

Hence, from equation ②

Average relative molecular mass of a gas mixture

$$= M_{avg.} = \frac{n_1 M_1 + n_2 M_2 + n_3 M_3 + ---}{n_1 + n_2 + n_3 + ----}$$

$$\text{or, } M_{avg.} = \frac{\sum nM}{\sum n} \quad ———— ⑥$$

Since one mole of any gas at the same pressure and temperature occupies the same volume then it follows that a percentage analysis by volume is also a percentage analysis by moles. If a percentage analysis is used then $\sum n = 100$. Thus, for air, the volumetric analysis is,

21% O_2, 78.05% N_2, 0.95% other gases

The relative molecular masses are,

$O_2 = 32$, $N_2 = 28$, other gases 39.9

For air then,

$$M_{avg} = \frac{\sum nM}{\sum n} = \frac{(21 * 32) + (78.05 * 28) + (0.95 * 39.9)}{100}$$

$$= \underline{28.95 \text{ kg}}$$

The density of a gas mixture:

From the volumetric analysis of a gas mixture determine the average relative molecular mass

$$M_{avg} = \frac{\sum nM}{\sum n} \quad ---- ①$$

By definition, one mole of the gas mixture will have a mass of M_{avg} kg.

The volume of one mole of the gas mixture at its pressure and temperature can be calculated as,

$$V = \frac{R_M T}{P} \quad ---- ②$$

From equation ① and ②

$$\text{Density} = \rho = M_{avg.} / V \text{, in } kg/m^3$$

From this,

$$\text{specific volume} = v = \frac{V}{M_{avg}} \text{, } m^3/kg$$

- The average value of the characteristic gas constant for a gas mixture :

Determine the average relative molecular mass of the gas mixture,

$$M_{avg.} = \frac{\sum nM}{\sum n} \quad ----①$$

For a gas, it has been shown that,

$$MR = R_M \quad ----②$$

From equations ① and ②

$$R_{avg.} = \frac{R_M}{M_{avg.}} \quad -----③$$

Molar heat capacity

Molar heat capacity at constant volume, C_v, is defined as the amount of heat which transfers to or from one mole of gas while the temperature changes by one degree and the volume remains constant.

Also,

Molar heat capacity at constant pressure, C_p, is defined as the amount of heat which transfers to or from one mole of gas while the temperature changes by one degree and the pressure remains constant.

In both cases the units are kJ/kgmol·K

Since there are M kg in one kgmol, then it follows that, $M \cdot c_v = C_v$ ---- ①

and $M \cdot c_p = C_p$ ---- ②

it has been shown that, for a gas,

$$c_p - c_v = R \quad \text{-----} ③$$

Multiplying equation ③ throughout by M, then,

$$M \cdot c_p - M \cdot c_v = MR$$

which from equations ① and ② becomes,

$C_p - C_v = MR$ ---- ④

Now $MR = R_M = 8.3143$ and substituting this into equation ④,

$C_p - C_v = 8.3143$ ----- ⑤

Also, $C_p / C_v = \gamma$, the adiabatic index, or specific heat ratio.

Multiplying top and bottom by M, then,

$$\frac{MC_p}{MC_v} = \gamma$$

or, from equations ① and ②,

$$\frac{C_p}{C_v} = \gamma \quad \text{------} ⑥$$

From eq. ⑤, $C_p = C_v + 8.3143$ — (5')

Substituting (5') into eq. ⑥,

$$\gamma = \frac{C_v + 8.3143}{C_v} \quad \text{-------} ⑦$$

Also, from eq. ⑤,

$C_v = C_p - 8.3143$ ----- (5'')

Substituting (5'') into eq. ⑥,

$$\gamma = \frac{C_p}{C_p - 8.3143} \quad \text{-------} ⑧$$

Average molar heat capacity of a gas mixture:

For any gas mixture let,

Total number of moles of gas mixture $= n_T$

Average molar heat capacity at constant volume of the gas mixture $= C_{v\,avg}$

Number of moles of each individual gas in the mixture $= n_1, n_2, n_3, \ldots$

Molar heat capacities at constant volume of each individual gas in the mixture $= C_{v_1}, C_{v_2}, C_{v_3}, \ldots$

Now the amount of heat required to raise n moles of gas through one degree rise of temperature while the volume remains constant $= n\,C_v$,
Hence, for the gas mixture, the amount of heat required to raise the temperature through one degree rise of temp..

$$= n_1 C_{v_1} + n_2 C_{v_2} + n_3 C_{v_3} + \cdots$$

$$= n_T C_{v\,avg} = (n_1 + n_2 + n_3 + \cdots) C_{v\,avg}$$

From this,

$$C_{v\,avg} = \frac{n_1 C_{v_1} + n_2 C_{v_2} + n_3 C_{v_3} + \cdots}{n_1 + n_2 + n_3 + \cdots}$$

or,
$$C_{v\,avg} = \frac{\sum n C_v}{\sum n} \quad \text{----} ①$$

By similar analysis, it can be shown that the average molar heat capacity at constant pressure is given by,

$$C_{p\,avg} = \frac{\sum n C_p}{\sum n}$$

Example:

(a) Given that standard pressure and temperature may be taken as 101.32 kPa and 0°C, respectively, calculate the volume of one kilogramme mole of a perfect gas.

(b) Assuming that air contains 21 % of oxygen by volume, the remainder being nitrogen, calculate:

(i) the average molecular mass of air;

(ii) the value of R, the characteristic gas constant in kJ/kg K;

(iii) the mass of one cubic metre of air at S.T.P.

Universal gas constant, $R_M = 8.3143$ kJ/kgmol·K.

Solution:- (a) $PV = nR_M T$ and for 1 kgmol $PV = R_M T$

$$\therefore V = \frac{R_M T}{P} = \frac{8.3143 * 273}{101.32} = 22.4 m^3$$

(b) i
$$M_{avg} = \frac{\Sigma nM}{\Sigma n} = \frac{(21 * 32) + (79 * 28)}{100}$$

$$= \frac{672 + 2212}{100} = \frac{2884}{100}$$

$$M_{avg} = 28.84 \text{ kg}$$

ii
$$R_{avg} = \frac{R_M}{M_{avg}} = \frac{8.3143}{28.84} = 0.288 \text{ kJ/kg·K}$$

iii
$$\rho = \frac{M_{avg}}{V} = \frac{28.84}{22.4} = 1.29 \text{ kg/m}^3$$

5/11

Boiler Burner Efficiency

Boiler burner efficiency can be expressed in terms of boiler burner heat losses. When these losses are in Btu per pound of fuel burned, the efficiency is calculated by

$$\eta_{bb} = \frac{HHV - \text{total losses}}{HHV} \times 100$$

There are six major boiler burner losses including:

1. the dry-gas loss (DGL),
2. the moisture loss (ML),
3. the moisture in combustion air loss (MCAL),
4. the incomplete combustion loss (ICL),
5. the unburned carbon loss (UCL), and
6. the radiation and unaccounted Loss (RUL).

To determine these losses the fuel and fluegas analysis must be available. The equations used for these calculations are listed in the following pages.

1. Dry-Gas Loss (DGL)

$$DGL = W_{dg}\, C_{p_g} (t_g - t_a) \quad \text{----(1)}$$

where, W_{dg} = dry flue gas weight (lb / lb of Fuel burned), it can be obtained by subtracting from the total gas weight, the unburned fuel (UF) and the moisture (W+9H) in the gases. That is

$$W_{dg} = W_a + 1 - \overset{Ash}{A} - UF - (W + 9H) \quad \text{----(2)}$$

The combination of $(\overset{Ash}{A} + UF)$ is frequently referred to as the solid refuse (W_r) which is in a unit of pound per pound of fuel burned. Because of air infiltration to the boiler system, the actual air (W_a) in above eq. cannot be accurately estimated.

As an alternative, the weight of dry flue gas is expressed in terms of flue gas data (orsat analysis test). The derivation of the equation is in the following:

$$W_{dg} = \underset{[1]}{\frac{\text{weight of dry gases}}{\text{lb of carbon burned}}} \times \underset{[2]}{\frac{\text{lb of carbon burned}}{\text{lb of fuel}}} \quad \text{--(3)}$$

The first term in the right-hand side is simply equal to:

$$[1] = \frac{44CO_2 + 32O_2 + 28CO + 28N_2}{12CO_2 + 12CO} \text{ ---- (4)}$$

The second term is the carbon in a pound of fuel minus the unburned fuel. That is,

$$[2] = C_f = C - UF \text{ ------ (5)}$$
$$= C - (W_r - Ash) \text{ ----- (5')}$$

Substituting these equations into Eq. (3) gives

$$W_{dg} = C_f \times \frac{44CO_2 + 32O_2 + 28CO + 28N_2}{12CO_2 + 12CO} \text{ --- (6)}$$

The dry-gas loss (DGL) is the longest among the six losses.

2. Moisture Loss (ML)

$$ML = (W + 9H)(h_s - h_w) \text{ ----(6)}$$

The term $(W+9H)$ represents the amount of moisture formed during combustion. It is due to mechanical moisture and combustion of the hydrogen element in the fuel. The term $(h_s - h_w)$ is the enthalpy change of the moisture and is approximated as

$$h_s - h_w = 1066 + 0.5\,t_g - t_f \text{ \underline{\underline{if}} } t_g > 575F \text{ --(7)}$$

and

$$h_s - h_w = 1089 + 0.46\,t_g - t_f \text{ \underline{\underline{if}} } t_g < 575F \text{ --(8)}$$

3. Moisture in Combustion Air Loss (MCAL)

$$MCAL = W_a\,\omega\,C_{p,w}(t_g - t_a) \text{ ----(9)}$$

where (ω) is the humidity ratio of air entering the boiler system and has a unit of pounds of water vapor per pound of dry air. The humidity ratio is a function of the dry-bulb and wet-bulb temperatures, and can be easily determined by using a psychrometric chart.

where, $W_a = W_{dg} + 8\left(H - \frac{O}{8}\right) - C_f - S - N$ --(10)

where C_f is defined by Eq. (5). Values of H; O; S; and N, are obtained from the fuel ultimate analysis and should have a unit of pounds per pound of fuel. Eq. (10) is based on the principle of mass conservation.

4. Incomplete-Combustion Loss (ICL)

$$ICL = W_{dg} \times \frac{28CO}{44CO_2 + 28CO + 28N_2 + 32O_2} \times 4380 \text{ --(11)}$$

5. Unburned Carbon Loss (UCL)

$$\begin{aligned} UCL &= (UF)(14600) \dashrightarrow (12) \\ \text{or,} \quad &= (W_r)(C_r^*)(14600) \end{aligned}$$

6. Radiation and Unaccounted-for Loss (RUL)

This loss is mainly due to radiation and incomplete combustion resulting in hydrogen and hydrocarbons in the flue gas. In practice, this loss ranges from 3 to 5%.

$^*C_r$ = Combustible in solid refuse

= UF / W_r.

Isam Ezzuldin BB-5

Thu., 13-12-2012

Ex: An old boiler test provides the data as follows:
Fuel ultimate analysis:

$C = 57.7\%$ $N = 1.0\%$ $Ash = 16.5\%$
$H = 3.7\%$ $S = 3.3\%$ $W = 12.0\%$
$O = 5.8\%$
$H.H.V = 11{,}000$ Btu/lb

Flue gas analysis:
$CO_2 = 13.0$; $O_2 = 7.0$ $CO = 1.0$ $N_2 = 79.0$

Refuse analysis:
$C_r = 20\%$

Flue gas temperature = 360 F , Air Temp. = 70°F

Air temperatures: Dry-bulb = 70 F
Wet-bulb = 60 F } $w = 0.0088\ lb_v / lb_{dair}$

The radiation and unaccounted-for loss is assumed to be 3%. Calculate the boiler efficiency for burner. Take C_{pg}, and C_{pv} as 0.24 Btu/lb-F and 0.47 Btu/lb-F respectively.

Solution:

First, the solid refuce is estimated per pound of coal burned. It is equal to the sum of the unburned carbon and the ash contained in the coal. That is,

$$W_r = UF + Ash$$

$$W_r = C_r W_r + Ash$$

$$= 0.2 W_r + 0.165$$

$W_r = 0.21$ lb/lb of coal. (approximated value)

Second, the dry flue gas is estimated by using eq. (5′) and eq. (6). It gives

$$W_{dg} = (0.577 - 0.206 + 0.165) \times \frac{44(13) + 32(7) + 28(1) + 28(79)}{12(13) + 12(1)}$$

$W_{dg} = 9.69$ lb/lb of coal

The actual air is determined using Eq. (10). Substituting the numerical values into the equation gives

$$W_a = 9.69 + 8\left(0.037 - \frac{0.058}{8}\right) - 0.536 - 0.033 - 0.01$$

$W_a = 9.35$ lb/lb of coal

With these results, the boiler burner (Furance) losses are calculated below:

1- DGL = (9.69)(0.24)(360−70)
= 674.4 Btu/lb of coal

2- ML = (0.12+9*0.037)(1089+0.46*360−70)
= 536.6 Btu/lb of coal.

3- MCAL = (9.35)(0.0088)(0.47)(360−70)
= 11.21 Btu/lb of coal.

4- $ICL = 9.69 * \frac{28(1.0)}{44(13)+28(1.0)+28(79)+32(7)} * 4380.$
= 391.4 Btu/lb of coal.

5- UCL = (0.21)(0.2)(14600) = 613.2 Btu/lb of coal

6- RUL = (0.03)(11000) = 330 Btu/lb of coal.

Then, the total losses are calculated as

$$\begin{aligned}\text{Total losses} &= DGL+ML+MCAL+ICL+UCL+RUL\\ &= 674.4+536.6+11.21+391.4+613.2+330\\ &= 2556.8 \text{ Btu/lb of coal.}\end{aligned}$$

Finally, the boiler furance efficiency is

$$= \frac{HHV - \text{total losses}}{HHV} \times 100$$

$$= \frac{11000 - 2556.8}{11000} \times 100$$

$$= 76.8\,\%$$

Isam Ezzuldin

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Flue Gas Analysis

1. Orsat Apparatus

The apparatus used for the volumetric analysis of dry flue gases is known as Orsat apparatus as shown below in Fig. (1).

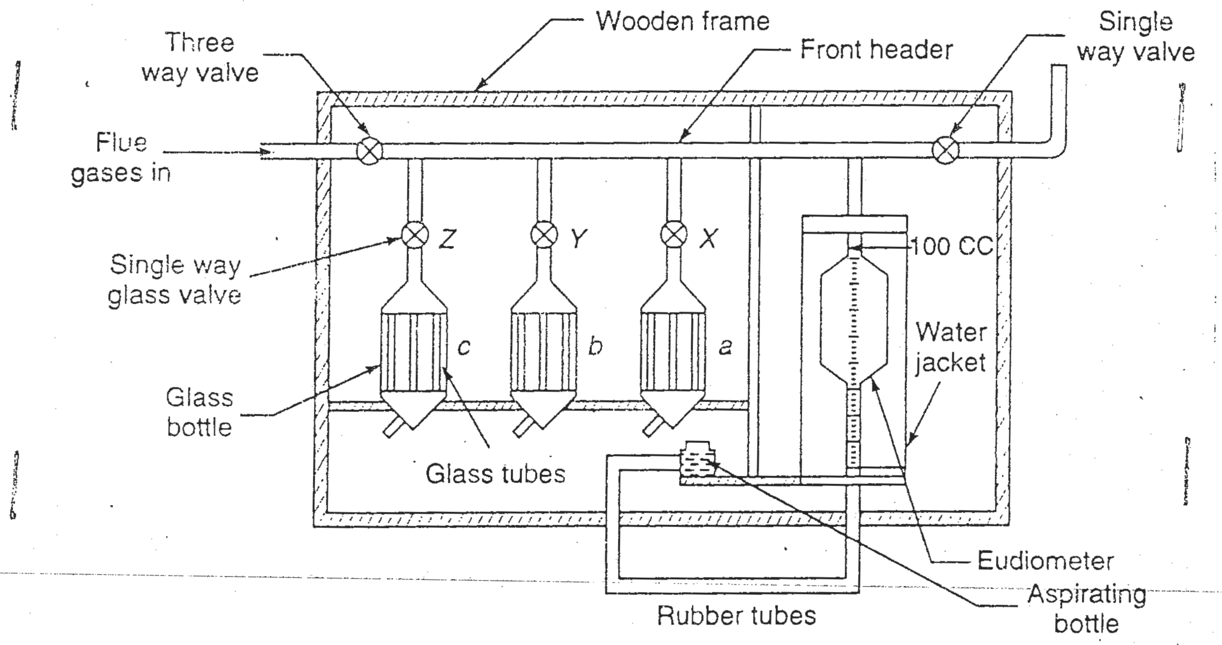

Fig. (1): Orsat Apparatus.

It consists of three flasks a, b and c each containing different chemicals for absorbing CO_2, O_2, and CO. The percentage of N_2 is obtained from the remainder. The percentage of SO_2 in the gases cannot be measured separately by the apparatus.

Absorbents used in flask 'a' are NaOH or KOH solution and this solution absorbs CO_2. The flask 'b' contains alkaline solution of pyrogallic acid and this solution absorbs O_2. The flask 'c' contains cuprous chloride which absorbs CO.

Keeping valves x, y and z closed, the three-way valve is opened and the aspirator bottle is moved down, so that the flue gas enters the eudiometer tube. The flue gas is drawn in until the level in the eudiometer reads zero. The three-way valve is closed and then the valve x of the flask 'a' is opened and the aspirator bottle is moved up and down several times pushing the gas into flask 'a' containing KOH solution, which absorbs the CO_2 gas. The flue gas is then taken into the eudiometer by lowering the aspirating bottle and the valve x is closed keeping the original level of solution. The aspirator is then brought near to eudiometer and placed at such a position that the water level in both is same and the reading of eudiometer tube is taken.

The difference in reading before absorbing and after absorbing CO_2 gives the percentage of CO_2 in the Flue gas. The procedure is repeated with the flasks 'b' and 'c' to find the percentage of O_2 and CO. The remainder of the flue gas after the absorption of CO is taken as N_2.

Absorbing the gases should be CO_2 first, O_2 second and finally CO as it is necessary because the absorbent used for O_2 may absorb some CO_2 and the percentage of CO_2 given by the apparatus would be less if O_2 is absorbed first and CO_2 afterwards. Correct sequence of absorption eliminates this difficulty. Flask a, b and c are made in duplicate joined together with a glass tube for proper mixing of gases with the absorbents. The eudiometer is surrounded by water to keep the temperature constant.

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Ex: An Orsat analysis of the exhaust from an engine running on benzole showed a CO_2 content of 15%, but no CO. Assuming that the remainder of the exhaust contains only oxygen and nitrogen, calculate the A/F ratio of the engine. The ultimate analysis of benzole is 90% C and 10% H_2.

Solution:

1 kg of fuel, consisting of 0.9 kg C and 0.1 kg H_2, can be written as 0.9/12 moles C and 0.1/2 moles H_2. Therefore considering 1 mole of dry exhaust gas, where the combustion equation is written as follows:

$$X\left(\frac{0.9}{12}C+\frac{0.1}{2}H_2\right)+YO_2+\frac{79}{21}YN_2$$

$$\longrightarrow 0.15\,CO_2+a\,O_2+(0.85-a)N_2+bH_2O$$

where, X : is the mass of fuel per mole D.E.G.
Y : is the moles of O_2 per mole D.E.G.
a : is the moles of excess O_2 per mole D.E.G.
b : is the moles of H_2O per mole D.E.G.

Then, Carbon balance : $\frac{0.9}{12}X=0.15 \Rightarrow X=2$ kg/mole D.E.G

Hydrogen balance: $0.05X = b \Rightarrow b = 2 * 0.05$
$= 0.1$

Oxygen balance: $2Y = 2 * 0.15 + 2a + b$
$Y = a + 0.2$ ------ ①

Nitrogen balance: $3.76 * 2 * Y = 2 * (0.85 - a)$
$\therefore Y = 0.226 - 0.266a$ ---- ②

Equating the equs. ① and ② for Y, gives

$$0.226 - 0.266a = 0.2 + a$$

$$\therefore a = 0.0206$$

$$Y = 0.2 + 0.0206 = 0.221$$

$\therefore O_2 = 0.221 * 32$ kg / mole D.E.G.

i.e. Air supplied $= \dfrac{0.221 * 32}{0.23} = 30.75$ kg/mole D.E.G.

Since $X = 2$, then, the fuel supplied per mole D.E.G. is 2 kg.

Then,

A/F ratio $= \dfrac{30.75}{2} = 15.375/1$

Calorific Value of Fuels

- The quantity ΔH_0 and ΔU_0 are approximated to in Fuel specifications by quantities called calorific values which are obtained by the combustion of the Fuels in a suitable apparatus. This may be of the constant volume type (Bomb Calorimeter), or constant pressure, steady flow type (Boys' Calorimeter).

- The energy transferred as heat to the surroundings (cooling water) per unit quantity of fuel when burned at constant volume with the H_2O product of combustion in the liquid phase is called the Higher (or Gross) Calorific Value (H.C.V.) at Constant Volume $Q_{gr,v}$. This approximates to $-\Delta U_0$ at 25°C with the H_2O in the liquid phase.

- The energy transferred as heat to the surroundings (cooling water) per unit quantity of fuel when burned at constant pressure with the H_2O products of combustion in the liquid phase is called the Higher (or Gross) Calorific Value (H.C.V.) at Constant Pressure, $Q_{gr,p}$. This approximates to $-\Delta H_0$ at a reference temperature of 25°C with the H_2O in the liquid phase.

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If the H_2O products are in the vapour phase the energy released is called the Lower (or Net) Calorific Value (L.C.V.) at Constant Pressure, $Q_{net,p}$.

where, For constant volume process

$$Q_{gr,v} = Q_{net,v} + m_c u_{fg} \qquad \text{---- (25)}$$

For constant pressure process

$$Q_{gr,p} = Q_{net,p} + m_c h_{fg} \qquad \text{--- (26)}$$

where, m_c = mass of condensate per unit quantity of fuel.

$u_{fg} = u_{fg}$ @ 25°C for H_2O = $\underline{2304.4 \text{ kJ/kg}}$

$h_{fg} = h_{fg}$ @ 25°C for H_2O = $\underline{2441.8 \text{ kJ/kg}}$

Practical Determination of Calorific Values

The methods for determining calorific value depend on the type of fuel; solid and liquid fuels are usually tested in a Bomb calorimeter, and gaseous fuels in a continuous flow apparatus such as the Boys' calorimeter.

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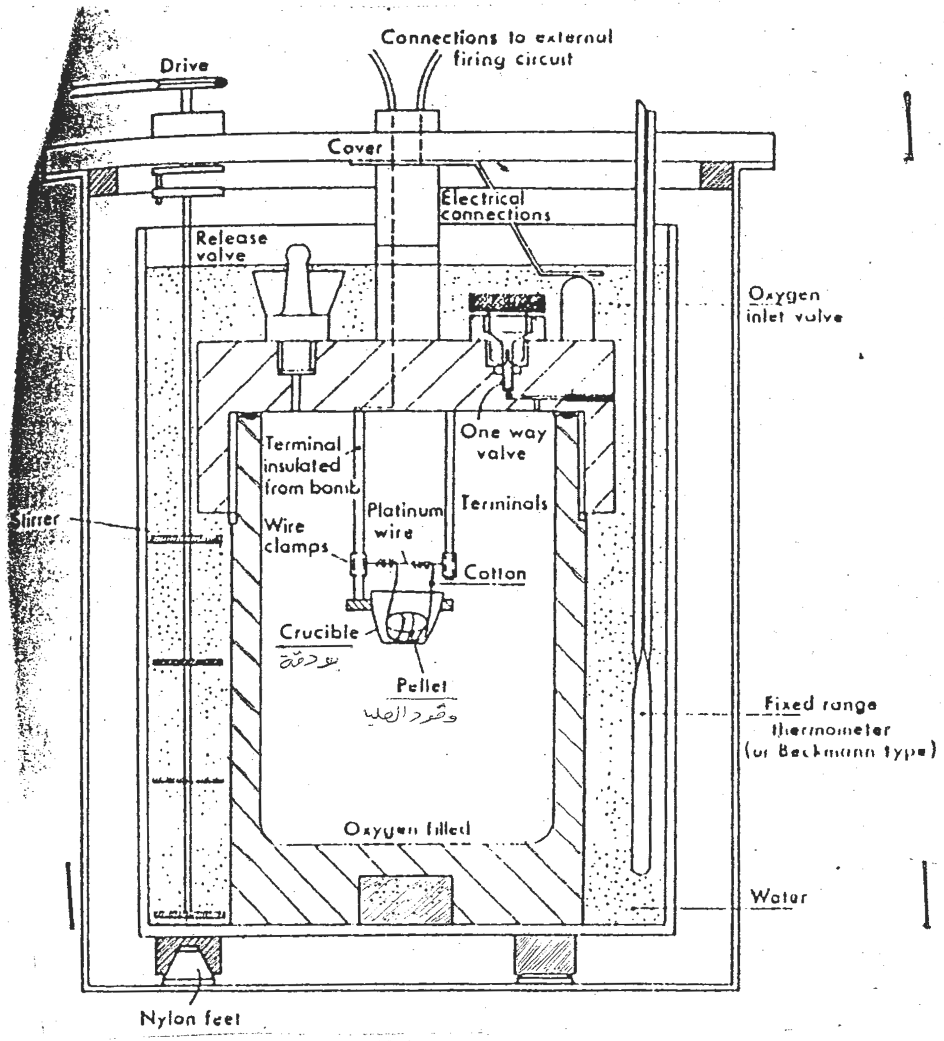
مسعر بوي

The bomb is a small stainless steel vessel in which a small mass of the fuel is held in a crucible, as shown in Fig. (6). If the fuel is solid, it is usually crushed, passed through a sieve, and then pressed into the form of a pellet in a special press. The pellet is ignited by fusing a piece of platinum or nichrome wire which is in contact with it. The wire forms part of an electric circuit which can be completed by a firing button, which is situated in a position remote from the bomb.

With a special form of press the pellet can be formed with the fuse wire passing through it. This facilitates the firing, particularly with some of the more difficult fuels. The crucible carrying the pellet is located in the bomb, a small quantity of distilled water is put into the bomb to absorb the vapours formed by combustion and to ensure that the water vapour produced is condensed, and the top of the bomb is screwed down.



Figure(6). Bomb Calorimeter.

Oxygen is then admitted slowly until the pressure is above 23 atmospheres. The bomb is located in the calorimeter and a measured quantity of water is poured into the calorimeter. The calorimeter is closed, the external connections to the circuit are made, and an accurate thermometer of the fixed range or the Beckmann type is immersed to the proper depth in the water. The water is stirred in a regular manner by a motor-driven stirrer, and temperature observations are taken every minute. At the end of the fifth minute the charge is fired and temperature readings are taken every ten seconds during this period. When the temperature readings begin to fall the frequency of readings can be reduced to every minute.

The measured temperature rise is corrected for various losses. The cooling loss is the largest, but corrections are also necessary for the heat released by the combustion of the wire itself, and for the formation of acids on combustion. The cooling correction can be determined graphically or by use of a formula developed by Regnault-Pfaundler. For most purposes only the correction for cooling need be applied.

If a liquid fuel is being tested, it is contained in a gelatine capsule and the firing may be assisted by including in the crucible a little paraffin of known calorific value.

The calculation for the test is then as follows;

Mass of fuel * Calorific value
= (mass of water + water equivalent of bomb) * corrected temperature rise * specific heat of water. ----- (27)

From this equation the calorific value of the fuel tested can be found.

Ex7: The following table gives the results of a bomb calorimeter test on a sample of coal. The mass of coal burned was (0.825g) and the total water equivalent of the apparatus was determined as (2500g). Calculate the calorific value of the coal in kJ/kg. The temperature rise is to be corrected according to the formula by Regnault and Pfaundler, but no correction need be made for the acids formed.

Prefiring Period Time	Temp °C	Heating Time	Temp °C	Cooling Period Time	Temp °C
0	25.730	t_1 6	27.340	t_n 10	27.880
1	25.732	t_2 7	27.880	11	27.878
2	25.734	t_3 8	27.883	12	27.876
3	25.736	t_4 9	27.885	13	27.874
4	25.738			14	27.872
t_0 5	25.740			15	27.870

The cooling correction is obtained as,

$$\text{Correction} = nv + \left(\frac{v_1 - v}{t_1 - t}\right)\left\{\sum_{1}^{n-1}(t) + \frac{1}{2}(t_0 + t_n) - nt\right\} \quad -(28)$$

where, n, is the number of minutes between the time of firing and the first reading after the temperature begins to fall from the maximum; v, is the rate of fall of temp. per minute during the prefiring period; v_1, is the rate of fall of temperature per minute after the maximum temperature; t and t_1 are the average temperatures during the prefiring and final periods respectively; $\sum_{1}^{(n-1)}(t)$, is the sum of the readings during the period between firing and the start of cooling; $\frac{1}{2}(t_0+t_n)$, is the mean of the temperature at the moment of firing and the first temperature after the rate of change of temperature becomes constant. The pre-firing and final periods are of the same duration.

Sol.:- In this example,

$$n = 10 - 5 = 5 \text{ min}$$

$$v = -\left(\frac{25.740 - 25.730}{5}\right) = -0.002 \text{ K/min}$$

(the negative sign indicates that the temperature was rising in the pre-firing period).

$$v_1 = \frac{27.880 - 27.870}{5} = 0.002 \text{ K/min}$$

$t = 25.735$°C and $t_1 = 27.875$°C

$$\sum_{1}^{(n-1)}(t) = 110.988\text{°C}, \text{ and } \frac{1}{2}(t_0+t_n) = \frac{25.740+27.880}{2} = 26.81\text{°C}$$

Substituting the values in the equation gives,

$$\text{Correction} = -5 * 0.002 + \left(\frac{0.002+0.002}{27.875-25.735}\right) * (110.988 + 26.81 - 5 * 25.735)$$

$$\text{Correction} = 0.00705 \text{ K}$$

Unconrected temperature rise $= t_n - t_o$

$= 27.880 - 25.740$

$= 2.14 K$

$\therefore$ Corrected temp. rise $= 2.14 + 0.00705 = 2.147 K$.

Then,

Heat released from 0.825 g coal $= 2.147 * 2500 * 4.187 * 10^{-3}$

$= 22.5 kJ$

i.e. Calorific Value $= \frac{22.5}{0.825 * 10^{-3}} = 27,273$ kJ/kg

For a gaseous fuel a continuous supply of the gas is metered and passed at constant pressure into the calorimeter, where it is burned in an ample supply of air. The products of combustion are cooled as nearly as possible to the initial temperature of the reactants by a continuously circulating supply of cooling water. The rates of flow are adjusted to burn gas at about 2.36 l/min, with water circulating at 2100 l/min for a gas of declared H.C.V. 18600 kJ/m³.

The gas pressure and temperature are measured as at 1013 mbar and 15°C. The temperature rise of the circulating water is measured, and the condensate from the products of combustion is collected. A test is carried out over a fixed time period. The water flow rate is measured and the condensate is weighed. Then

(Volume of fuel @ 1013 mbar and 15°C) * (Calorific value)

= (mass of water circulated) * $\overset{C_p}{\text{specific heat}}$ * (temperature rise of water) ...... ㉙

The calorific value of the fuel is obtained in MJ/m^3 of gas. All of this done by Boys' Calorimeter as shown below.

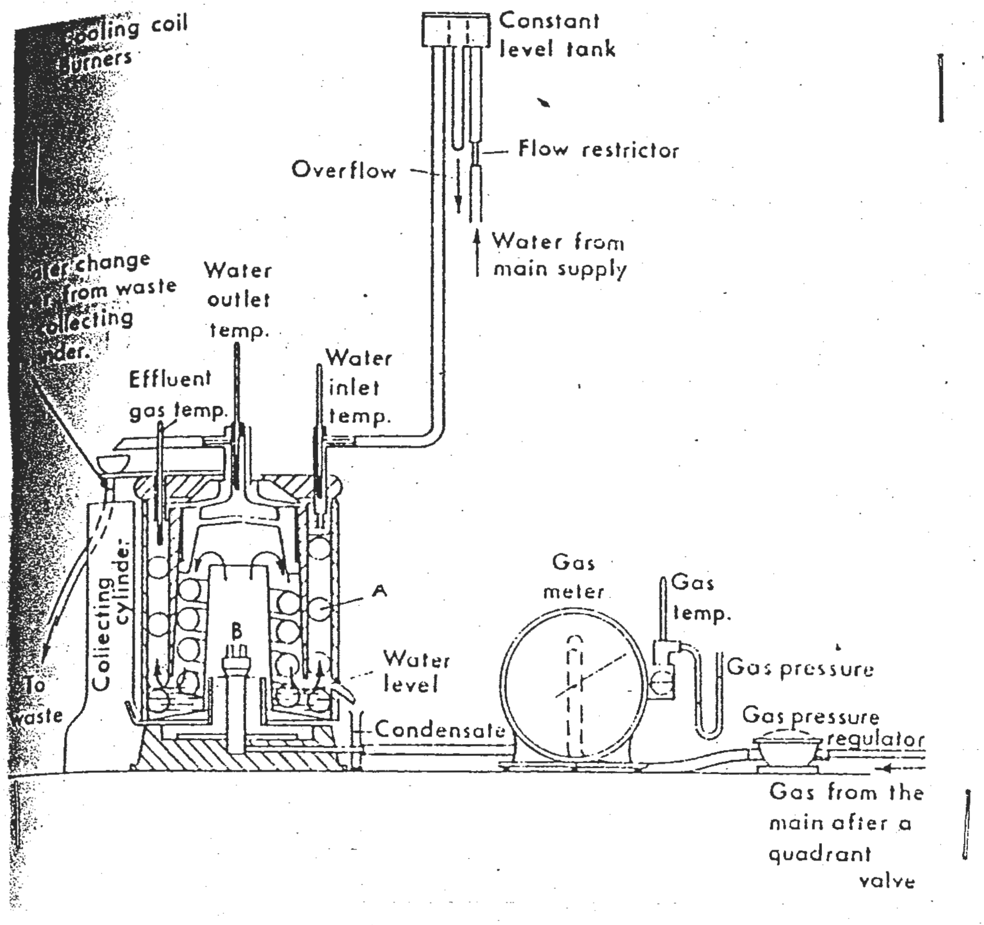


Figure (7). Boys' Calorimeter.

Ex8: The calorific value of a supply of town gas was determined using a Boys' calorimeter and was found to be 20 MJ/m³. The condensate collected during the test amounted to 840 g for every m³ of gas burned. Calculate the L.C.V. of the gas.

Sol.:-

Using eq. (26),

$$Q_{net,p} = Q_{gr,p} - m_c * h_{fg}$$

$$\therefore, Q_{net,p} = 20 - 840 * 10^{-6} * 2441.8$$

$$= 17.95 \ MJ/m^3.$$

Ex: In a bomb calorimeter test on petrol the H.C.V. was determined and found to be 46900 kJ/kg. If the fuel contains 14.4% H_2 by mass, calculate the L.C.V..

Sol.:- combustion equation of H_2 is,

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$\therefore 4 \text{ kg } H_2 + 32 \text{ kg } O_2 \rightarrow 36 \text{ kg } H_2O$$

or, 1 kg H_2 gives 9 kg H_2O,

$\therefore$ 0.144 kg H_2 gives $0.144 * 9 = 1.296$ kg H_2O

Then using eq. (25)

$$\therefore Q_{net,v} = 46900 - 1.296 * 2304.4$$

$$= 43910 \text{ kJ/kg}$$