UNIT-1 COMBUSTION THERMODYNAMICS

1.1 Introduction

All conventional fossil fuels, whether, solid, liquid or gaseous, contain basically carbon and hydrogen which invariably react with the oxygen in the air forming carbon dioxide, carbon monoxide or water vapour. The heat energy released as a result of combustion can be utilized for heating purposes or for generation of high pressure steam in a boiler or as power from an engine or a gas turbine.

The solid fuels are burned in beds or in pulversied from suspended in the air stream. The liquid fuels are burned either by vaporising and mixing with air before ignition, when they behave like a gaseous fuel. The gaseous fuels are either burned in burners when the fuel and air are premixed or the fuel and air flow separately in to a burner or a furnace and simultaneously mix together as combustion proceeds.

The Kg-mole or gram-mole is widely used in combustion calculations as a unit of weight. The molecular weight of any substance in kg represents one kilogram mole or 1K mole. 1Kmol of hydrogen has a mass of 2.016Kg and 1Kmol of carbon has a mass of 12Kg.

Consider a reaction

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad 1.1$$

$$(12+4.032) + 64 \rightarrow 44 + 2\,(2.032 + 16)$$

16.032kg of methane reacts with 64Kg of oxygen to form 44kg of carbon dioxide and 36.032kg of water. We can also simply state that 1Kmol of methane reacts with 2Kmol of oxygen to form 1Kmol of carbon dioxide and 2K mol of water, this has advantage of permitting easy conversion between the mass and volumetric quantities for the gaseous fuel and the product of combustion. If the gases are considered ideal then according to Avogadro hypothesis, all gases contain the same number of molecules per unit volume. It implies that 1K mole of any gaseous substance occupies the volume of 22.4m^3 at NTP i.e., 1.013bar and 273K.

$$CH_4 + 20_2 \rightarrow CO_2 + 2H_2O \qquad 1.2$$

1 volume of methane reacts with 2 volume of oxygen to form one volume of CO_2 and two volumes of H_2O. Therefore in any reactions, the mass in confirmed but the no. of mol or volumes may not be considered.

(i) $C + O_2 \rightarrow CO_2$

On mass basis $(12) + (32) \rightarrow (44)$

1 Mol (C) + 1 Mol (O_2) $\rightarrow$ 1 Mol (CO_2)

(ii) $2C + O_2 \rightarrow 2CO$

On mass basis (24) + (32) → (56)

Volume basis 2 Mol (C) + 1 Mol (O_2) → 2Mol (CO)

(iii) $2C + O_2 \rightarrow 2CO_2$

On mass basis (56) + (32) → (88)

2 Mol (CO) + 1 Mol (O_2) → 2 Mol (CO_2)

1.2 Combustion Stoichometry

A balanced chemical equation for complete Combustion of the reactions with no excess air in the product is known as a stiochiometric equation. A stiochiometric mixture of the reactants is one in which the molar proportions of the reactants are exactly as given by the stiochiometric coefficients, so that no excess of any constituent is present. In general a chemical reaction may be written as

$$aA + bB \quad - \quad cC + dD \qquad 1.3$$

Where the reactants A and B react to form the products C and D. The small letters a, b, c and d are known as the stiochiometric coefficients.

For the combustion of any fuel the most common oxidizer is air which is a mixture of 21% O_2 and 79% N_2 (on volume basis). One mol of oxygen is accompanied by 79/21 (3.76) mol of Nitrogen. The Chemical equation for the stiochiometric combustion of carbon with air is written as

$$C + O_2 + 3.76N_2 \rightarrow CO_2 + 3.76N_2 \qquad 1.4$$

The minimum amount of air required for the complete combustion of a fuel is known as theoretical air. However in practice it is difficult to achieve complete combustion with theoretical air. Therefore fuel requires some excess air for different application and may vary from 5% ~ 20% and in gas turbine it may go up to 400% of theoretical quantity.

1.3 Theoretical air required for complete combustion.

If the fuel composition is known, the requirement of oxygen or air can be calculated either by mass balance or by mole method.

Consider a equation

$$C + O_2 \rightarrow CO_2 \qquad 1.5$$

(12) + (32) → (44)

Or 1 + 8/3 → 11/3

Or 1 Kg C + 8/3 Kg O_2 → 11/3 kg CO_2

Similarly

$2C + O_2 \rightarrow 2CO$ 1.6

$2(12) + (32) \rightarrow 2(28)$

Or 1 Kg C + 32/24 Kg O_2 $\rightarrow$ 56/24 kg CO

Or 1 Kg C + 4/3 Kg O_2 $\rightarrow$ 7/3 kg CO

Similarly

1 Kg CO + 4/7 Kg O_2 $\rightarrow$ 11/7 kg CO_2 1.7

On molal basis

1K mol C + 1K mol O_2 $\rightarrow$ 1K mol CO_2

1K mol C + ½ K mol O_2 $\rightarrow$ 1K mol CO

1K mol C + ½ K mol O_2 $\rightarrow$ 1K mol CO_2

1.4 Conversion of Gravimetric analysis to volumetric basis and vice versa

If the composition of fuel is given on gravimetric (or weight) basis it can be converted to volumetric (or mole) basis as follows. Divide the weight of each constituents of the mixture by its molecular weight. This will give the relative volume (or mole) of each constituents. Add all the relative volumes of the constituents then,

$$\frac{\text{Indivisual (relative) volume of the constituents}}{\text{Total volume of all the constituents}} \times 100$$

will give the %age by volume of each constituents in the fuel.

If the volumetric composition of a fuel is given, it can be converted to gravimetric (or weight) basis as follows. Multiply the indivisual volume of each constituent by its molecular weight. This will give relative weight of each constituent. Add all the relative weights of the constituents then

$$\frac{\text{Indivisual weight of the constituents}}{\text{Total(reative)weights of the constituents}} \times 100$$

will give the %age by weight of each constituent in the fuel.

1.4.1 Calculation of the minimum amount of air for a fuel of known composition.

Example 1

Calculate the minimum volume of air required to burn one Kg of coal having the following composition by weight

C = 72.4%, H_2 5.3%, N_2 = 1.81, O2 = 8.5%, moisture 7.2%
S = 0.9% and ash 3.9%

On weight basis:

Taking 1kg coal as basis weight of oxygen required to burn 1kg of coal

$$C + O_2 \rightarrow CO_2$$

0.724 x 32/12 = 1.93 kg

0.53x 16/2 = 0.424 kg

0.009x32/32 = 0.009 kg

Total O_2 = 2.363 kg per kg of coal

But 0.085kg O_2 is available in coal, therefore O_2 required

= 2.363 – 0.085 = 2.278kg per Kg of coal.

Air contains 23% of oxygen by weight. Therefore the weight of the air supplied is

2.278x 100/23 = 9.9 kg per kg of coal

Density of air required at NTP

$P v = mRT$

$P = m/v\, RT = \rho RT$,

$\rho = \frac{\text{Molecular weight}}{\text{Volume}}$

$= P/RT = 1.013\text{x}10^5/287\text{x}273 = 1.29\ kg/m^3$

Therefore volume of air required = 9.9(kg)/1.29(kg) = 7.67 m^3

On mole basis

Consider 100kg of coal

C	=	72.4/12	= 6.03K mol,	O_2 = 8.5/32	= 0.265K mol
H_2	=	5.3/2	= 2.65K mol,	H_2O = 7.2/18	= 0.4K mol
N_2	=	1.8/28	= 0.064K mol,	S = 0.9/32	= 0.028K mol

1K mol C + 1K mol O_2 → 1Km CO_2

Therefore 6.03 K mol of carbon requires
6.03 K mol of oxygen

1 K mol H_2 + ½ K mol O_2 → 1K mol H_2O
H2 - 2.65 x ½ = 1.325K mol
S - 0.028x1 = 0.028
Total O_2 required 6.03 + 1.325 + 0.028 = 7.383

The oxygen present in coal 0.265K mol

Net O_2 required = 7.383 – 0.265 = 7.118K mol

Air required

7.118x100/21 = 33.89K mol / 100kg of coal = 0.3389K mol / 1kg coal

Volume of air supplied
0.3389K mol/kg X 22.4m^3 = 7.59m^3/kg of coal

Example 2

Calculate the volumetric analysis of the flue gases when coal burns with 20% excess air from the previous calculation the actual air required 33.89K mol/100kg coal. Therefore the actual air is
33.89 x 120/100 = 40.67K mol/ 100 kg coal

The amount of N_2 associated with this

40.67 x 79/100 = 32.13K mol

The amount of O_2 present 40.67 x 21/100 = 8.54K mol

The actual amount of O_2 required was 7.118K mol excess O_2 will appear in exhaust gas = 8.54 – 7.118 = 1.422K mol.

Therefore:

CO_2 = 6.03K mol
SO_2 = 0.028K mol
N_2 = 32.13K mol (air) + 0.064 (fuel)
= 32.194K mol
O_2 = 1.422K mol os excess oxygen.

Therefore the Total volume = (6.03 + 0.028 + 32.194 + 1.422)
= 39.674K mol

The volumetric composition of the gas

CO_2 = (6.03/39.674) x 100 = 15.12%

SO_2 = (0.028/39.674) x 100 = 0.07%

N_2 = (32.13/39.674) x 100 = 81.15%

O_2 = (1.422/39.674) x 100 = 3.58%

1.5 Calculation of the composition of fuel and excess air supplied from the exhaust gas analysis:

Some times the composition of fuel is unknown and it becomes necessary to judge whether the amount of air supplied is sufficient or not, or excess. This can be obtained by analyzing the sample of exhaust gases.

Example 3

The composition of dry flue gases obtained by burning a liquid fuel containing only hydrogen and carbon is CO_2 10.7%, O_2 5.1%, N_2 84.2%. Calculate the composition of fuel by weight and excess air used.

Solution: consider 100K mol of dry flue gases. They will contain 10.7K mol of O_2 (from CO_2) + 5.1K mole of (as max. oxygen) = 15.8K mol

Using nitrogen balance the actual air used 84.2 x 100/79 = 106.58K mol of dry flue gases and oxygen in the air supplied 106.58 x 21/100 = 22.38K mol. Therefore the amount of O_2 present in the water produced by the combustion of H_2 is 22.38 – 15.8 = 6.58K mol O_2. We know that 1 K mole of H_2 combines with ½ K mol O_2 to produce water. Therefore the amount of hydrogen present is 6.58x2 = 13.16K mol/100K mol of dry flue gases, and the carbon present is 12X10.7 = 128.4kg/100K mol of dry flue gas. Therefore the composition of fuel (by weight) is 128.4kgC and 26.32Kg H_2 on the %age basis.

C = (128.4/(128.4+26.32) x 100 = 82.99%

H = (26.32/(128.4+26.32) x 100 = 17.01%

Excess air supplied

The amount of O_2 required to burn 10.7K mol C is 10.7K mol and to burn 13.16K mol H_2 is 13.16 X ½ = 6.58

Total O_2 required = 10.7 + 6.58 = 17.28K mol/100K mol of dry flue gases

%age of excess air = (22.38 – 17.28)/(17.28) x 100 = 29.5%

1.6 Dew point of products:

The product of combustion containing water vapour are known as wet products. The water vapour present in combustion product is cooled down to a point of condensation the vapour turn in to liquid and volume will be reduced. Knowing the partial pressure exerted by the water before condensing, it is possible to find the saturation temp. corresponding to partial pressure from the steam tables.

1.7 Flue gas analysis

A fuel has the following %age volumetric analysis

H_2 = 48 CH_4 : 26, CO_2 : 11, CO : 5, N_2 = 10

The %age volumetric analysis of the dry exhaust gases in CO_2:8.8, O_2: 5.5, N_2: 85.7

Determine the air/fuel ratio by volume if air contains 21% O_2 by volume

Solution: the chemical equation for the reaction of 100 moles of fuel gas with air may be written as

$$48H_2 + 26CH_4 + 11CO_2 + 5CO + 10N_2 + x\,(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cO_2 + dN_2$$

Carbon balance	(C)	$\rightarrow$	26 + 11 + 5	=	a = H_2
	H_2	$\rightarrow$	48 + 52	=	b = 100
	O_2	$\rightarrow$	11 + 2.5 + x	=	a + c (i)
	N_2	$\rightarrow$	10 + 3.76x = d		(ii)

Solving (i) and (ii) we, have

From (i) $11 + 2.5 + x = 100/2 + a + c$

$13.5 + x = 50 + a + c$

Adding $\underline{\quad 10 + 3.76x = d}$

$23.5 + 4.76x = 50 + a + c + d$

Or $a + c + d = 4.76x – 26.5$

% CO_2 by volume in dry gas

$(a/a+c+d) \times 100 = 8.8$

or $(42/4.76x – 26.5) = 0.088$

$4.76x = 503.77$

$$AF = \frac{\text{Total mol air}}{\text{Total mol fuel}} = \frac{503.77}{100} = 5.038\%$$

Example 4

A blast furnace gas has the following volumetric analysis H_2 CO-24%, CH_4 – 2%, CO_2-6%, O_2-3% and N_2-56%

Determine the Ultimate gravimetric analysis

Given volumetric analysis, H_2 – 9%, CO-24%, CH_4 – 2%, CO_2-6%, O_2-3% and N_2-56%

Solution: The volumetric analysis may be converted into mass or granite metric analysis by completing the table as follows:

Constituent	Volume in 1m3 of flue gas (a)	Molecular mass (b)	Proportional mass (c)=(a)x(b)	Mass in kg per kg of the gas (d)=(c)/ Σ ©	% by mass = (d)x100
CO	0.24	28	6.72	6.72/18.48 = 0.36	36%
CH_4	0.02	16	0.32	0.32/18.48 = 0.0173	1.73%
CO_2	0.06	44	2.64	264/18.48 = 0.142	14.2%
O_2	0.03	32	0.96	0.96/18.48 = 0.0519	5.19%
N_2	0.56	14	7.84	7.84/18.48 = 0.42	42%
			Σc = 18.48	Σ (d) = 1	100

The volumetric analysis of flue gas components becomes
CO-0.36, CH_4 – 0.0173, CO_2- 0.142, O_2-0.0519 and N_2-0.42

Example 5

Determine the fuel gas analysis and air fuel ratio by weight when fuel oil with 84.9% carbon, 11.4% hydrogen, 3.2% sulphur, 0.4% oxygen and 0.1% ash by weight is burnt with 20% excess air, assume complete combustion.

Solution: Consider 1kg of fuel

Oxygen required / Kg of fuel

For burning of 1kg C - 0.849 x32/12

For burning of 1kg H - 0.114 x16/2

For burning of 1kg S - 0.032 x32/32

Total O_2 required is 3.208 kg.

Amount of O_2 contained in the fuel = 0.004Kg

Net O_2 supplied / kg of fuel = 3.208 – 0.004

= 3.204 kg O_2

Net air supplied = 3.204x100/23 = 13.93 kg/kg of fuel

When 20% excess air supplied

Total air supplied = 13.93 x 1.2 = 16.716 kg/kg of fuel.

N_2 actually supplied = 16.716 x 77/100 = 12.871 kg/kg of fuel

O_2 actually supplied = 16.716 x 23/100 = 3.845 kg/kg of fuel

Total free O_2 in fuel gas = 3.845 – 6.204

= 0.641 kg/kg of fuel

Total free N_2 in fuel gas = 12.87 kg/kg of fuel

Flue gas analysis:

C	converted to CO_2	=	0.849x44/12	=	3.113 kg CO_2
H	converted to H_2O	=	0.114x18/2	=	1.026 kg H_2O
S	converted to SO_2	=	0.032x64/32	=	0.064 kg SO_2

Flue gas / kg of fuel:

= 3.113 + 1.26 + 0.064 + 0.641 + 12.871
CO_2 H_2O SO_2 O_2 N_2
= 17.715kg.

Therefore:

CO_2 = (3.113/17.715)x100 = 17.573%

SO_2 = (0.064/17.715)x100 = 0.36%

O_2 = (0.641/17.715)x100 = 3.618%

H_2O = (1.026/17.715)x100 = 5.79%

N_2 = (12.871/17.715)x100 = 72.656%

Air fuel mixture ratio is = 16.716 : 1

Example 6

A blast furnace gas has the following volumetric analysis.

H_2 = 9%, CO = 24%, CH_4 = 2%, CO_2 = 6%, O_2 = 3% and N_2 = 56 %

Determine the ultimate gravimetric analysis.

Solution:

Total H2 in the blast furnace gas.

% volumetric analysis = $9H_2 + 2H_4$

Proportional mass = % volumetric analysis X mol. Mass of element

= (9x2) + (2x4) = 18 + 8 = 26 kg.

Total ‘C’ in the blast furnace gas.

% of volumetric analysis	= 24C + 2C + 6C
Proportional mass	= (24+2+6) x 12
	= 384 kg

Total O_2 in the blast furnace gas

% of volumetric analysis	= 24xO + $6O_2$ + $3O_2$
Proportional mass	= (24+16) x 9 (32)
	= 672 kg

Total N_2 in the blast furnace gas

% of volumetric analysis	= 56 N_2
Proportional mass of N_2	= 56 x 28 = 1568 Kg.

Total weight of blast furnace gas:

= 384kg C + 26kg H_2 + 672kg O_2 + 1568kg N_2
= 2650kgs

Gravimetric %age compositon:

C	=	(384/2650)x100 =	14.49%
H_2	=	(26/2650)x100 =	0.98%
O_2	=	(672/2650)x100 =	25.36%
N_2	=	(1568/2650)x100 =	59.17%

Example 7

The analysis of coal used in a boiler trial is as follows. 82% carbon, 6% hydrogen, 4% oxygen, 2% moisture and 8% ash. Determine the theoretical air required for complete combustion of 1kg of coal. If the actual air supplied is 18kg per kg of coal the hydrogen is completely burned & 80% carbon burned to CO_2 ,the reminder is CO, Determine the volumetric analysis of the dry products of combustion.

Solution: For complete combustion.

O_2 required is

For carbon - 0.82 = 2.186 kg of O_2

For hydrogen - 0.006 = 0.48 kg of O_2

Total O_2 required = 2.666kg.

Net O_2 supplied = Total O_2 required – O_2 present in the fuel

= 2.66 – 0.004

= 2.662 kg/kg of coal

Theoretical minimum air required for complete combustion [C burns to CO_2 totally]

Air supplied = 2.626x100/23 = 11.417 kg/kg of coal

Flue gas analysis:

But actually only 80% carbon is burns to CO_2

CO_2 = 0.8 x 0.82 x44/12 = 2.405kg of CO_2

20% carbon is burnt to CO

CO = 0.2 x 0.82 x 28/12 = 0.383 kg of CO

O_2 actually required for 80% carbon burnt to CO_2

= 0.8 x 0.82 x 3232/12 = 1.749 kg of O_2

O_2 actually required for 20% carbon burnt to CO

= 0.2 x 0.82 x 16/12 = 0.219 kg of O_2

O_2 required by Hydrogen:

= 0.06 x 8 = 0.48 kg of O_2.

H_2O produced = 0.06 x 9 = 0.54 kg of H_2O

But actual air supplied = 18kg

Actually O_2 supplied = 18 x23/100 = 4.14 kg of O_2

Free O_2 in the flue gas = 4.14 + 0.04 – 1.749 – 0.219 – 0.48

= 1.732 kg of O_2/kg of coal

N_2 in the flue gas = 18x77/100 = 13.86 kg/kg of coal

Volumetric analysis of the dry products of combustion.

CO_2	= (2.405/44)x 100	=	0.0546m /K. mol
CO	= (0.383/28) x 100	=	0.0137 m^3/K.mol
O_2	= (1.732/32)x 100	=	0.0541m^3/K.mol
N_2	= (13.86/28)x 100	=	0.495m^3/K.mol

In % of volume:

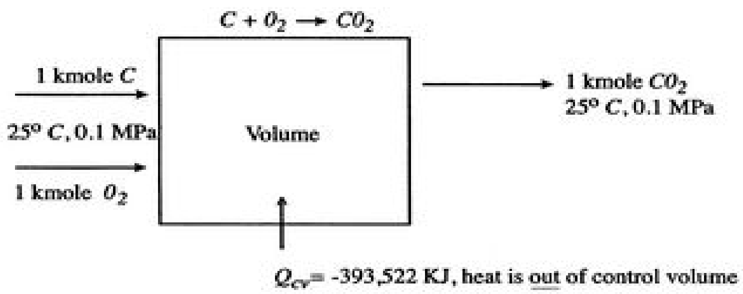
CO_2	= (0.0546/0.6174)x 100	=	8.84%
CO	= (0.0137/0.6174)x 100	=	2.22%
O_2	= (0.0541/0.6174)x 100	=	8.76%
N_2	= (0.495/0.6174)x 100	=	80.70%

1.8 Enthalpy of reaction

Enthalpy of a reaction is defined as the difference between the enthalpy of the products at a specified state and the enthalpy of the reactants at the same state for a complete reaction. For combustion process, the enthalpy of a reaction is usually referred to as the “enthalpy of combustion” it is obviously a very useful property for analyzing the combustion processes of fuels. However there are so many different fuels and fuel mixtures that is not practical to list enthalpy of combustion values for all possible cases. Besides, the enthalpy of combustion is not of much use when the combustion is incomplete. Therefore a more practical approach would be have a more fundamentally property to represent the chemical energy of an element or compound at some reference state. This property is the “enthalpy of formation” which can be viewed as the enthalpy of a substance at a specified state due to its chemical composition. To establish a starting point it is assigned the enthalpy of formation for all stable elements such as O_2, N_2, H_2 and C a value of zero at standard reference state of 25°C and 1 atm. For all stable compounds.

In a chemical reaction bonds are broken in the reactants and new bonds formed in the products. Energy is required to break bonds and energy is released when bonds are formed. The energy associated with a chemical reaction depends on the number and type of bonds broken and/or formed.

Every chemical species has a certain amount of "heat content," or enthalpy, H, which cannot be measured. However, differences in enthalpy can be measured. The net energy change for a reaction performed at constant pressure is the enthalpy change for the reaction. This enthalpy change, ΔH, has units kJ/mol and is defined:



[C + H (fuel)] + [O_2 + N_2 (Air)] -> (Combustion Process) -> [CO_2 + H_2O + N_2 (Heat)]

where

C = Carbon, H = Hydrogen, O = Oxygen, N = Nitrogen

(1) $\Delta H = H(products) - H(reactants)$

If energy is given off during a reaction, such as in the burning of a fuel, the products have less heat content than the reactants and ΔH will have a negative value; the reaction is said to be exothermic. If energy is consumed during a reaction, ΔH will have a positive value; the reaction is said to be endothermic.

The enthalpy change for a chemical change is independent of the method or path by which the change is carried out as long as the initial and final substances are brought to the same temperature. This observation, known as HESS'S LAW, has important practical utility.

Thermochemical equations may be treated as algebraic equations: they may be written in the reverse direction with a change in the sign of ΔH – even though the reverse reaction may not actually occur; they may be added and subtracted algebraically; the equation and associated ΔH value may be multiplied or divided by factors. Hess's Law allows the calculation of enthalpy changes that would be difficult or impossible to determine directly, i.e. by experiment.

The enthalpy change for the reaction:

(2) $2C\ (s) + O_2\ (g) \rightarrow 2CO\ (g)$

cannot be determined directly because carbon dioxide will also form. However, □H can be measured for:

(3) $C\ (s) + O_2\ (g) \rightarrow CO_2\ (g)$ $\Delta H = -393.5$ kJ

(4) $2CO\ (g) + O_2\ (g) \rightarrow 2CO_2\ (g)$ $\Delta H = -566.0$ kJ

Multiplying equation (3) by 2 gives equation (5), and reversing equation (4) gives equation (6):

(5) $2C\ (s) + 2O_2\ (g) \rightarrow 2CO_2\ (g)$ $\Delta H = -787.0$ kJ

(6) $2CO_2\ (g) \leftrightarrow 2CO\ (g) + O_2\ (g)$ $\Delta H = +566.0$ kJ

Adding equations (5) and (6) gives the desired information:

(2) $2C\ (s) + O_2\ (g) \rightarrow 2CO\ (g)$ $\Delta H = -221.0$ kJ

For a reaction in which a compound is formed from the elements, the enthalpy change is called the heat of formation, ΔH_f^o, for the compound. The superscript "o" indicates standard conditions of one atmosphere pressure. Equation (2) and (3) are such reactions. Some others:

(7) $S\ (s) + O_2\ (g) \rightarrow SO_2\ (g)$ $\Delta H = -296.9$ kJ

(8) $Mg\ (s) + Cl_2\ (g) \rightarrow MgCl_2\ (s)$ $\Delta H = -641.8$ kJ

In reactions (2), (3), (7), and (8) ΔH for the reaction is ΔH_f^o for the compound. For the reaction:

(9) $2S\ (s) + 3O_2\ (g) \rightarrow 2SO_3\ (g)$ $\Delta H = -790.4$ kJ

the heat of reaction is associated with the formation of two moles of SO_3. But heat of formation is per mole of compound, so ΔH_f^o for SO_3 is half of –790.4, or –395.2 kJ.

Extensive listings of heats of formation are available in handbooks. With these values of ΔH_f^o, you can calculate virtually any heat of reaction. The heat of a reaction is the sum of ΔH_f^o values for the products minus the sum of ΔH_f^o values for the reactants. Expressed as a formula:

(10) $$\Delta H_{rxn} = \Sigma \Delta H^{\circ}_{f\ products} - \Sigma \Delta H^{\circ}_{f\ reactants}$$

Heats of formation for several compounds are given below. Note that the phase of the compound

is important when choosing a ΔH_f
for a free element is zero.

STANDARD HEATS OF FORMATION, ΔH_f^o, kJ/mole, at 25 °C

$AgCl$ (s)	–127.1	$Ca(OH)_2$ (s)	–986.1	K_3PO_4 (aq)	–2002.9
$AgNO_3$ (aq)	–100.7	$Ca(OH)_2$ (aq)	–1002.9	K_2SO_4 (aq)	–1409.2
$AlCl_3$ (s)	–695.4	HCl (g)	–92.3	$MgCl_2$ (aq)	–797.1
$AlCl_3$ (aq)	–1027.2	HCl (aq)	–167.4	$Mg(NO_3)_2$ (aq)	–875.1
$Al(OH)_3$ (s)	–1272.8	H_2O (g)	–241.8	$NaCl$ (aq)	–407.1
$Al_2(SO_4)_3$ (aq)	–3753.5	H_2O (l)	–285.8	$NaHCO_3$ (s)	–947.7
$BaCl_2$ (aq)	–873.2	H_3PO_4 (aq)	–1294.1	$NaNO_3$ (aq)	–446.2
$Ba(NO_3)_2$ (aq)	–951.4	H_2SO_4 (l)	–814.0	$NaOH$ (aq)	–469.4
$BaSO_4$ (s)	–1473.2	H_2SO_4 (aq)	–888.0	Na_2SO_4 (aq)	–1387.0
$CaCl_2$ (aq)	–877.8	KOH (aq)	–481.2	$ZnCl_2$ (aq)	–487.4

<u>EXAMPLE</u>: Using ΔH_f^o data calculate the heat of reaction for:

(11) $AgNO_3$ (aq) + $NaCl$ (aq) → $AgCl$ (s) + $NaNO_3$ (aq)

$$\Delta H^o = [\Delta H_f^o\ AgCl\ (s) + \Delta H_f^o\ NaNO_3\ (aq)] - [\Delta H_f^o\ AgNO_3\ (aq) + \Delta H_f^o\ NaCl\ (aq)]$$

$$= [(-127.0) + (-446.2)] - [(-100.7) + (-407.1)]$$

$$= [-573.2] - [-507.8] = -573.2 + 507.8 = -65.4\ kJ$$

<u>EXAMPLE</u> Using ΔH_f^o data calculate the heat of reaction for

(12) 2 $AgNO_3$ (aq) + $MgCl_2$ (aq) → 2 $AgCl$ (s) + $Mg(NO_3)_2$ (aq)

$$\Delta H^o = [2\ \Delta H_f^o\ AgCl\ (s) + \Delta H_f^o\ Mg(NO_3)_2\ (aq)] - [2\ \Delta H_f^o\ AgNO_3\ (aq) + \Delta H_f^o\ MgCl_2\ (aq)]$$

$$= [2(-127.0) + (-875.1)] - [2(-100.7) + (-797.1)]$$

$$= [-1129.1] - [-998.5] = -1129.1 + 998.5 = -130.6\ kJ$$

Note: the values of ΔH_f^o
chemical equation.

are multiplied by the stiochiometric coefficients from the balanced

(13) $2C (s) + O_2 (g) \rightarrow 2CO (g)$ $\Delta H = -221.0$ kJ

(14) $C (s) + O_2 (g) \rightarrow CO_2 (g)$ $\Delta H = -393.5$ kJ

(15) $2H_2 (g) + O_2 \rightarrow 2H_2O (g)$ $\Delta H = -483.6$ kJ

(16) $2H_2 (g) + O_2 \rightarrow 2H_2O (l)$ $\Delta H = -571.8$ kJ

(17) $CaO (s) + CO_2 (g) \rightarrow CaCO_3 (s)$ $\Delta H = -178.1$ kJ

(18) $2Ca (s) + O_2 (g) \rightarrow 2CaO (g)$ $\Delta H = -1271.0$ kJ

Using Hess' Law with appropriate equations from (13)-(18), above, calculate ΔH for each of the following reactions:

1) $H_2O (l) \rightarrow H_2O (g)$

2) $C (s) + H_2O (g) \rightarrow CO (g) + H_2 (g)$

3) $Ca (s) + H_2O (g) \rightarrow CaO (s) + H_2 (g)$

4) $CO (g) + 1/2\ O_2 (g) \rightarrow CO_2 (g)$

5) $2Ca (s) + 2C (s) + 3O_2 (g) \rightarrow 2CaCO_3 (s)$

Using heats of formation values from page T-56 calculate ΔH for each of the following reactions:

6) $2Al (s) + 3Cl_2 (g) \rightarrow 2AlCl_3 (s)$

7) $2Al (s) + 3H_2SO_4 (aq) \rightarrow Al_2(SO_4)_3 (aq) + 3H_2 (g)$

8) $2Al (s) + 3ZnCl_2 (aq) \rightarrow 2AlCl_3 (aq) + 3Zn (s)$

9) $3BaCl_2 (aq) + Al_2(SO_4)_3 (aq) \rightarrow 3BaSO_4 (s) + 2AlCl_3 (aq)$

10) $Na_2SO_4 (aq) + BaCl_2 (aq) \rightarrow BaSO_4 (s) + 2NaCl (aq)$

11) $BaCl_2 (aq) + 2AgNO_3 (aq) \rightarrow 2AgCl (s) + Ba(NO_3)_2 (aq)$

12) $Ca(OH)_2 (aq) + 2HCl (aq) \rightarrow CaCl_2 (aq) + 2H_2O (l)$

13) $2Al(OH)_3 (s) + 3H_2SO_4 (aq) \rightarrow Al_2(SO_4)_3 (aq) + 6H_2O (l)$

14) $AlCl_3 (aq) + 3NaOH (aq) \rightarrow Al(OH)_3 (s) + 3NaCl (aq)$

15) $3KOH (aq) + H_3PO_4 (aq) \rightarrow K_3PO_4 (aq) + 3H_2O (l)$

Answers to Problems

1) +44.1 kJ	9) –76.9 kJ
2) +131.3 kJ	10) –19.2 kJ
3) –393.7 kJ	11) –130.8
4) –283.0 kJ	12) –111.7
5) –2414.2 kJ	13) –258.7
6) –1390.8 kJ	14) –58.7 kJ
7) –1089.5 kJ	15) –122.6
8) –592.2 kJ	

1.9 Internal Energy of Combustion: It is defined as the difference between the internal energy of the products and the internal energy of the reactants when complete combustion occurs at a given temperature and pressure.

$$U_c = U_p – U_R$$

$$= \quad \Sigma_p\, n_e\, (h_f + \Delta h – pv) - \Sigma_R\, n_i\, (h_f + \Delta h – pv)$$

1.10 Combustion efficiency

It is defined as the ratio of ideal fuel-air to the actual fuel-air ratio

$$\eta_{comb} = \frac{(F/A)_{ideal}}{(F/A)_{actl}}$$

Example 8

Consider the following reaction, which occurs in a steady state, steady flow processes.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\ (l)$$

The reactants and products are each at total pressure of 0.1Mpa and 25^oC. Determine the heat transfer for per K mol of fuel entering the combustion chamber.

Solution : using the values of enthalpy of formation

$$Q = \quad h_f \ = \Sigma_p\, n_e h_f \ - \ \Sigma_R\, n_i h_f$$

$\Sigma_R\, n_i h_f = (h_f)\ CH_4 = -74873KJ$

$\Sigma_p\, n_e h_f = (h_f)\ CO_2 + 2\ (h_f)_{H2O\ (l)}$

$= - 393522+2\ (-2852830) = - 965182KJ$

Therefore Q = - 965182 – (-74873) = - 890309KJ

Example 9

A small gas turbine uses C8H18 ® as fuel and 400% theoretical air. The air and fuel enters at 25^oC and the products of combustion leaves at 900K. The output of the engine and the fuel consumption are measured and it is found that the specific fuel consumption is 0.25kg/Sec of fuel per MW out put. Determine the heat transfer from the engine per K mol of fuel. Assume complete combustion

Solution:

The combustion equation is

$$C_8H_{18} + 4\,(12.5)O_2 + 4\,(12.5)\,(3.76)N_2 \quad - \quad 8CO_2 + 9H_2O + 37.5O_2 + 188N_2$$

By first law

$$Q + \Sigma_R\, n_i\,(h_f + \Delta h); = W + \Sigma_p\, n_e\,(h_f + \Delta h)$$

$\Sigma_R\, n_i\,(h_f + \Delta h) = (h_f)_{C8H18} =$ 250105KJ/K mol fuel at 25^oC

Considering the products

$$\Sigma_p\, n_e\,(h_f + \Delta h) = nCO_2\,(h_f + \Delta h)_{CO2} + nH_2O\,(h_f + \Delta h)_{H2O} + nO_2\,(\Delta h)_{O2} + nN_2\,(\Delta h)_{N2}$$

h_f of O_2, N_2 = O Δh = Enthalpy of formation from 298^{o}K to 900K

Therefore $\Sigma_p\, n_e\,(h_f + \Delta h) = 8\,(-393522+288030)+9(-241826+21892)$
$+37.5(19249)+188(18222) = -755769$KJ/K mol fuel.

$$W = \frac{1000(KW)}{0.25} \quad X \quad \frac{114\ Kg}{K\ mol} = 456920KJ/K\ mol$$

Therefore $Q = -755769+456920-(-250105) = -48744$KJ/K mol fuel

CHAPTER 1

Testing of I.C.Engines

1.1. Introduction: - The basic task in the design and development of I.C.Engines is to reduce the cost of production and improve the efficiency and power output. In order to achieve the above task, the engineer has to compare the engine developed by him with other engines in terms of its output and efficiency. Hence he has to test the engine and make measurements of relevant parameters that reflect the performance of the engine. In general the nature and number of tests to be carried out depend on a large number of factors. In this chapter only certain basic as well as important measurements and tests are described.

1.2. Important Performance Parameters of I.C.Engines:- The important performance parameters of I.C. engines are as follows:

(i) Friction Power,

(ii) Indicated Power,

(iii) Brake Power,

(iv) Specific Fuel Consumption,

(v) Air – Fuel ratio

(vi) Thermal Efficiency

(vii) Mechanical Efficiency,

(viii) Volumetric Efficiency,

(ix) Exhaust gas emissions,

(x) Noise

1.3. Measurement of Performance Parameters in a Laboratory

1.3.1. Measurement of Friction Power:- Friction power includes the frictional losses and the pumping losses. During suction and exhaust strokes the piston must move against a gaseous pressure and power required to do this is called the “pumping losses”. The friction loss is made up of the energy loss due to friction between the piston and cylinder walls, piston rings and cylinder walls, and between the crank shaft and camshaft and their bearings, as well as by the loss incurred by driving the essential accessories, such as water pump, ignition unit etc.

Following methods are used in the laboratory to measure friction power:

(i) Willan’s line method;

(ii) From the measurement of indicated power and brake power;

(iii) Motoring test;

(iv) Retardation test;

(v) Morse Test.

1.3.1.1. Willan’s Line Method:- This method is also known as fuel rate extrapolation method. In this method a graph of fuel consumption (vertical axis) versus brake power (horizontal axis) is drawn and it is extrapolated on the negative axis of brake power (see Fig. 1).The intercept of the negative axis is taken as the friction power of the engine at

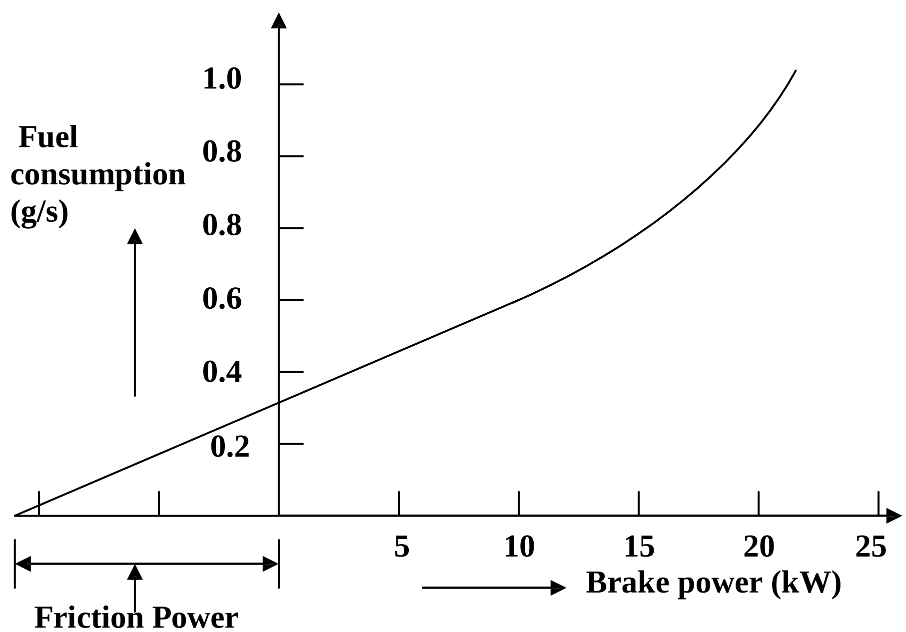


Figure.1 Willan’s line method

that speed. As shown in the figure, in most of the power range the relation between the fuel consumption and brake power is linear when speed of the engine is held constant and this permits extrapolation. Further when the engine does not develop power, i.e. brake power = 0, it consumes a certain amount of fuel. This energy in the fuel would have been spent in overcoming the friction. Hence the extrapolated negative intercept of the horizontal axis will be the work representing the combined losses due to friction, pumping and as a whole is termed as the frictional loss of the engine. This method of measuring friction power will hold good only for a particular speed and is applicable mainly for compression ignition engines.

The main draw back of this method is the long distance to be extrapolated from data between 5 and 40 % load towards the zero line of the fuel input. The directional margin of error is rather wide because the graph is not exactly linear.

1.3.1.2.From the Measurement of Indicated Power and Brake Power:- This is an ideal method by which friction power is obtained by computing the difference between the indicated power and brake power. The indicated power is obtained from an indicator diagram and brake power is obtained by a brake dynamometer. This method requires elaborate equipment to obtain accurate indicator diagrams at high speeds.

1.3.1.3.Morse Test:- This method can be used only for multi – cylinder IC engines. The Morse test consists of obtaining indicated power of the engine without any elaborate equipment. The test consists of making, in turn, each cylinder of the engine inoperative and noting the reduction in brake power developed. In a petrol engine (gasoline engine), each cylinder is rendered inoperative by *"shorting"* the spark plug of the cylinder to be made inoperative. In a Diesel engine, a particular cylinder is made inoperative by cutting off the supply of fuel. It is assumed that pumping and friction are the same when the cylinder is inoperative as well as during firing.

In this test, the engine is first run at the required speed and the brake power is measured. Next, one cylinder is cut off by short circuiting the spark plug if it is a petrol engine or by cutting of the fuel supply if it is a diesel engine. Since one of the cylinders is cut of from producing power, the speed of the engine will change. The engine speed is brought to its original value by reducing the load on the engine. This will ensure that the frictional power is the same.

If there are k cylinders, then

Total indicated power
when all the cylinders are working $= ip_1 + ip_2 + ip_3 + \ldots\ldots\ldots\ldots.. + ip_k = \sum_{j=1}^{k} ip_j$

We can write $\sum_{j=1}^{k} ip_j = B_t + F_t$ ………………………………………..(1)

where ip_j is the indicated power produced by j th cylinder, k is the number of cylinders,

B_t is the total brake power when all the cylinders are producing power and F_t is the total frictional power for the entire engine.

If the first cylinder is cut – off, then it will not produce any power, but it will have frictional losses. Then

we can write $\sum_{j=2}^{k} ip_j = B_1 - F_t$……………………………………..(2)

where B_1 = total brake power when cylinder 1 is cut - off and

F_t = Total frictional power.

Subtracting Eq. (2) from Eq. (1) we have the indicated power of the cut off cylinder. Thus

$$ip_1 = B_t – B_1 \quad \text{……………………………………..(3).}$$

Similarly we can find the indicated power of all the cylinders, viz., ip_2, ip_3, …..ip_k. Then the total indicated power is calculated as

$$(ip)_{total} = \sum_{j=1}^{k} ip_j \quad \text{……………………………………….(4)}$$

The frictional power of the engine is therefore given by

$$F_t = (ip)_{total} – B_t \quad \text{……………………………………(5)}$$

The procedure is illustrated by some examples worked out at the end of the chapter.

1.4. MEASUREMENT OF INDICATED POWER

The power developed in the cylinder is known as Indicated Horse Power and is designated as IP.

The IP of an engine at a particular running condition is obtained from the indicator diagram. The indicator diagram is the *p-v* diagram for one cycle at that load drawn with the help of indicator fitted on the engine. The construction and use of mechanical indicator for obtaining *p-v* diagram is already explained.

A typical *p-v* diagram taken by a mechanical indicator is shown in Figure 2.

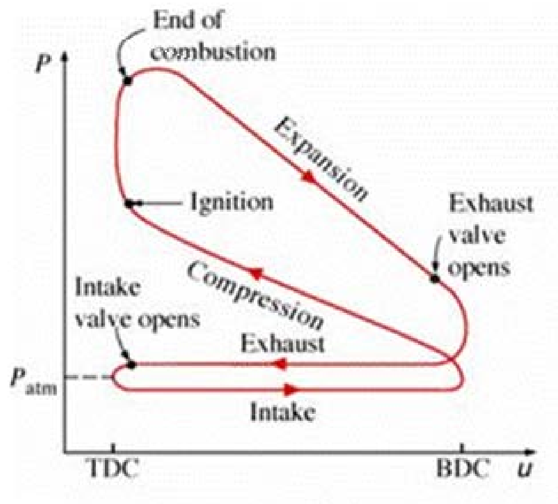


Figure.2 p-v diagram taken by mechanical indicator

The areas, the positive loop and negative loop, are measured with the help of a planimeter and let these be A_p and A_n cm^2 respectively, the net positive area is (A_p – A_n). Let the actual length of the diagram as measured be *L* cm, then the average height of the net posiive area is given by

$$h=(A_p-A_n)/L \quad \text{in centimetre}$$

The height multiplied by spring-strength (or spring number) gives the indicated mean effective pressure of the cycle.

$$Imep=(A_p-A_n)*S/L \qquad .....(6)$$

Where *S* is spring scale and it is defined as a force per unit area required to compress the spring through a height of one centimeter (N/m^2/cm).

Generally the area of negative loop A_n is negligible compared with the positive loop and it cannot be easily measured especially when it is taken with the spring used for taking positive loop. Special light springs are used to obtain the negative loop. When two different springs are used for taking the *p-v* diagram of positive and negative loop, then the net indicated mean effective pressure is given by

$$P_m=A_p*S_p/L-A_n*S_n/L \quad .....(7)$$

Where S_p = Spring strength used for taking *p-v* diagram of positive loop, (N/m^2 per cm)
S_n = Spring strength used for taking *p-v* diagram of negative loop, (N/m^2 per cm)
A_p = Area in Cm2 of positive loop taken with spring of strength S_p
A_n = Area in Cm2 of positive loop taken with spring of strength S_n
Sometimes spring strength is also noted as spring constant.

The IP developed by the engine is given by

$$IP=P_mLAn/L \quad .....(8)$$

Where 'n' is the number of working strokes per second.

The explanation of this expression is already given in the last chapter.

1.5. MEASUREMENT OF B.P

Part of the power developed in the engine cylinder is used to overcome the internal friction. The net power available at the shaft is known as brake power and it is denoted by B.P. The arrangement used for measuring the BP of the engine is described below:

(a) Prony Brake. The arrangement of the braking system is shown in Figure 3. It consists of brake shoes made of wood and these are clamped on to the rim of the brake wheel by means of the bolts. The pressure on the rim is adjusted with the help of nut and springs as shown in Fig 2. A load bar extends from top of the brake and a load carrier is attached to the end of the load bar. Weight kept on this load carrier is balanced by the torque reaction in the shoes. The load arm is kept horizontal to keep the arm length constant.

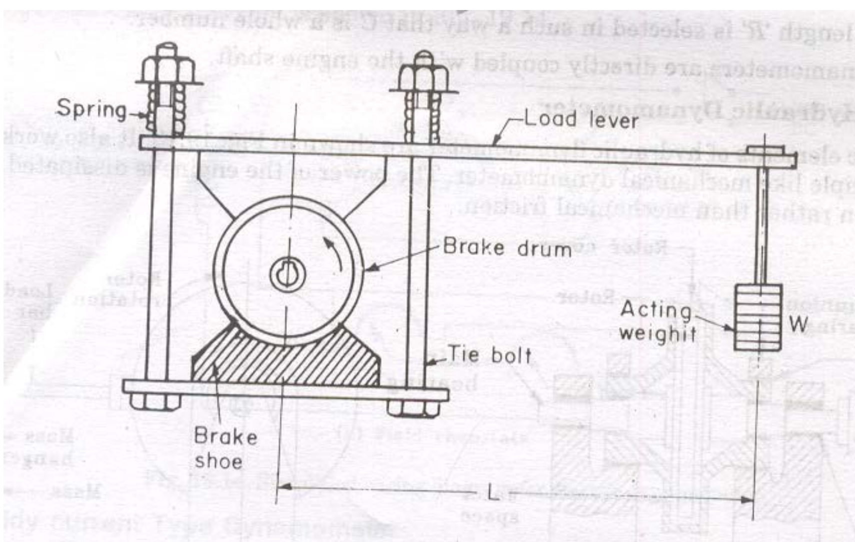


Fig. Prony-brake arrangement.

Figure.3

The energy supplied by engine to the brake is eventually dissipated as heat. Therefore, most of the brakes are provided with a means of supply of cooling water to the inside rim of the brake drum.

The BP of the engine is given by

B.P (brake power) = $2*\pi*N*T/60$ watts $=2*\pi*N*T/60*1000$ Kw ….. (9)

Where T = $(W.L)$ (N-m)

Where W = Weight on load carrier, (N)

And L = Distance from the centre of shaft to the point of load-meter in meters.

The prony brake is inexpensive, simple in operation and easy to construct. It is, therefore, used extensively for testing of low speed engines. At high speeds, grabbing and chattering of the band occur and lead to difficulty in maintaining constant load. The main disadvantage of the prony brake is its constant torque at any one band pressure and therefore its inability to compensate for varying conditions.

1.5.1 Hydraulic Dynamometer.

The BP of an engine coupled to the dynamometer is given by

B.P (brake power) = 2*π*N*W*R/60*1000 = WN(2*π*R/60*1000) Kw

The working of a prony brake dynamometer is shown in figure 4

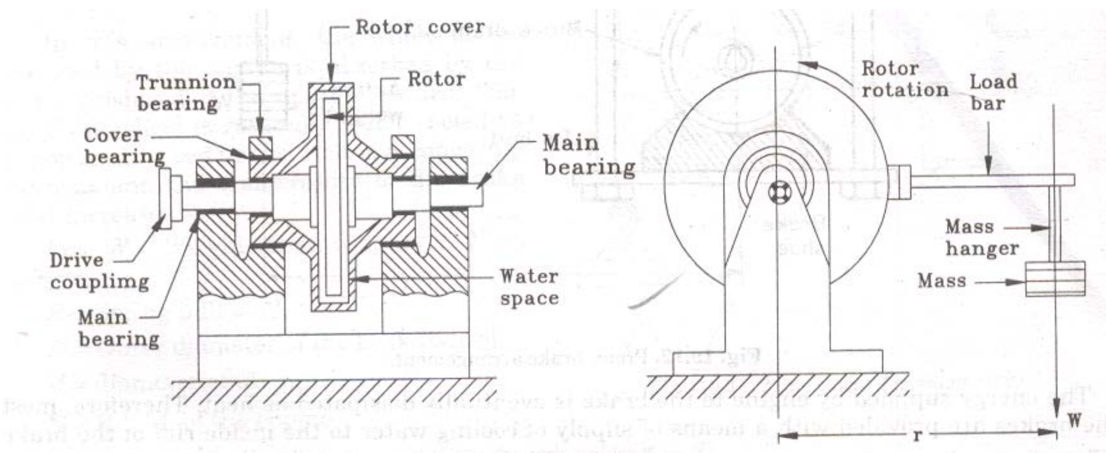


Figure.4 Hydraulic dynamometer

In the hydraulic dynamometer, as the arm length (R) is fixed, the factor [2 R/(60x1000)] is constant and its value is generally given on the name plate of the dynamometer by the manufacturer and is known as brake or dynamometer constant. Then the BP measured by the dynamometer is given by

$$B.P = \frac{WN}{K} \quad .....(10)$$

Where W = Weight measured on the dynamometer, N

K = Dynamometer constant (60*1000/2*pi*R)

and N = RPM of the engine.

The arm length 'R' is selected in such a way that K is a whole number.
These dynamometers are directly coupled with the engine shaft.

1.5.2 Electric Dynamometer:

The electric generator can also be used for measured BP of the engine. The output of the generator must be measured by electrical instruments and corrected for generator

efficiency. Since the efficiency of the generator depends upon load, speed and temperature, this device is rather inconvenient to use in the laboratory for obtaining precise measurement. To overcome these difficulties, the generator stator may be supported in ball bearing trunnions and the reaction force exerted on the stator of the generator may be measured by a suitable balance. The tendency to rotate or the reaction of the stator will be equal and opposite to the torque exerted on the armature, which is driven by the engine which is shown in
Figure 5.

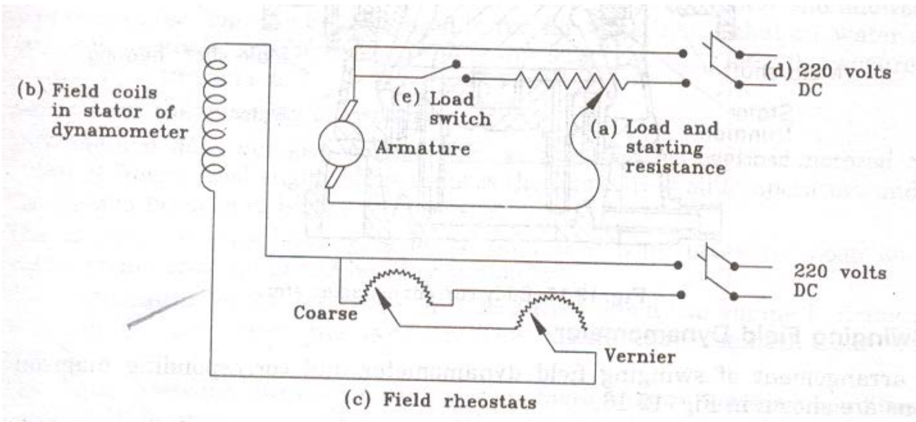


Fig. Simplified wiring diagram for electric dynamometer.

Figure.5

The electric dynamometer can also used as a motor to start and drive, the engine at various speeds.

There are other types of dynamometers like eddy current dynamometer, fan brake and transmission dynamometers used for measurement of large power output.

1.5.3 Eddy current Type Dynamomter

The 'eddy-current' dynamometer is an effect, a magnetic brake in which a toothed steel rotor turns between the poles of an electromagnet attached to a trunioned stator. The resistance to rotation is controlled by varying the current through the coils and hence, the strength of the magnetic field. The flux tends to follow the smaller air gaps at the ends of the rotor teeth and eddy currents are set up within the metal of the pole pieces, resulting in heating the stator. The heat energy is removed by circulating water through a water jacket formed in the stator. Figure 6 shows the "Heenan eddy-current dynamometer".

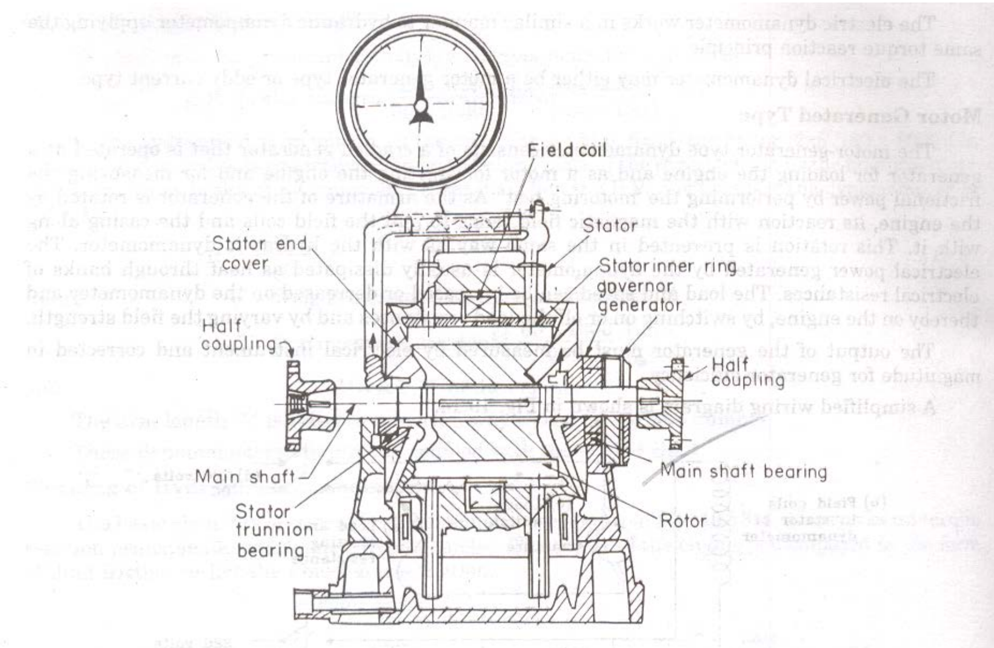


Fig. Eddy-current dynamometer.

Figure.6

The power output of eddy-current dynamometer is given by the equation where *C* is eddy-current dynamometer constant.

The advantages of eddy-current dynamometer are listed below:

1. High absorbing power per unit weight of dynamometer.
2. Level of field excitation is below 1% of the total power handled by the dynamometer.
3. The torque development is smooth as eddy current developed smooth.
4. Relatively higher torque is provided under low speed conditions.
5. There is no limit to the size of dynamometer.

1.5.4 Swinging Field Dynamometer

The arrangement of swinging field dynamometer and corresponding diagram of electric connections are shown in Figure 7.

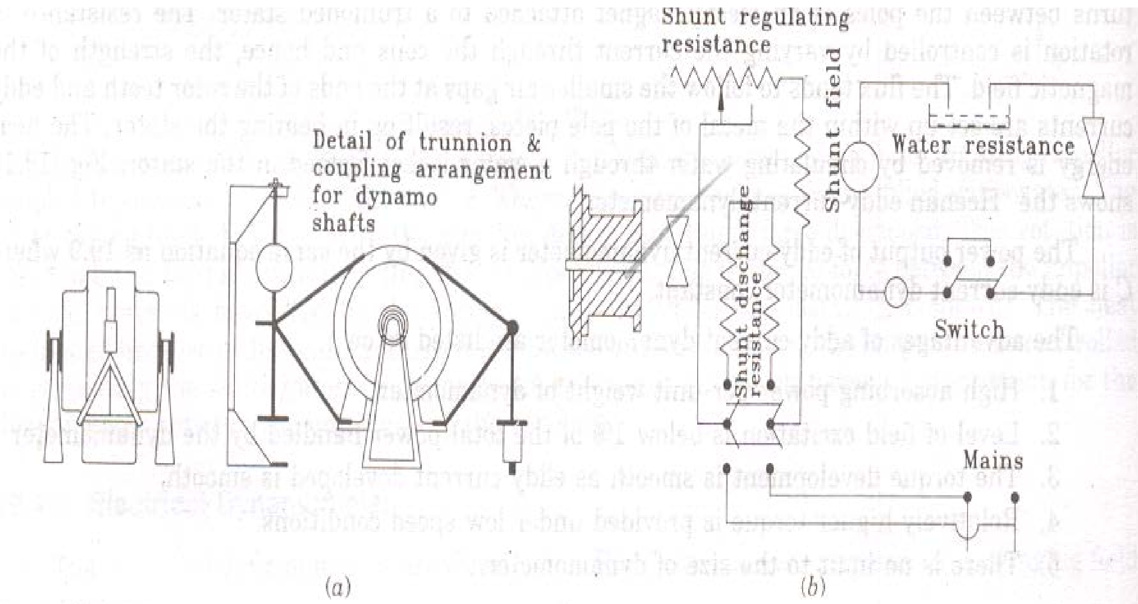


Fig. (*a*) Swinging-field dynamometer (*b*) Diagram of connections for swinging-field electrical dynamometer.

Figure.7

A swinging field DC dynamometer is basically a DC shunt motor. It is supported on trunnion bearings to measure the reaction torque that the outer casing and field coils tend to rotate with the magnetic drag. Therefore, it is named as "Swinging field". The Torque is measured with an arm and weighting equipment in the usual manner.

The choice of dynamometer depends on the use for which the machine is purchased. An electric dynamometer is preferred as it can operate as motor used for pumping or generator for testing the engine. Also, engine friction power can also be measured by operating the dynamometer in the motoring mode.

An eddy-current or hydraulic dynamometer may be used because of low initial coast and an ability to operate at high speeds. The armature of the electric dynamometer is large and heavy compared with eddy-current dynamometer and requires strong coupling between dynometer and engine.

1.6 MEASUREMENT OF I.P OF MULTI-CYLINDER ENGINE (MORSE TEST)

This method is used in multi-cylinder engines to measure I.P with out the use of indicator. The BP of the engine is measured by cutting off each cylinder in turn. If the engine consists of 4-cylinders, then the BP of the engine should be measured four times cutting each cylinder turn by turn. This is applicable to petrol as well as for diesel engines. The cylinder of a petrol engine is made inoperative by "shorting" the spark plug whereas in case of diesel engine, fuel supply is cut-off to the required cylinder.

If there are '*n*' cylinders in an engine and all are working, then

$$(B.P)_n = (I.P)_n - (F.P)_n \quad \ldots..(11)$$

Where F.P is the frictional power per cylinder.

If one cylinder is inoperative then the power developed by that cylinder (IP) is lost and the speed of the engine will fall as the load on the engine remains the same. The engine speed can be resorted to its original value by reducing the load on the engine by keeping throttle position same. This is necessary to maintain the FP constant, because it is assumed that the FP is independent of load and depends only on speed of the engine.

When cylinder "1" is cut off; then

$$(B.P)_{n-1} = (I.P)_{n-1} - (F.P)_n \quad \text{.....(12)}$$

By subtracting Eq. (23.7) from Eq.(23.6), we obtain the IP of the cylinder which is not firing i.e., $(B.P)_n - (B.P)_{n-1} = (IP)_n - (IP)_{n-1} = I.P_1$
Similarly IP of all other cylinders can be measured one by one then the sum of IPs of all cylinders will be the total IP of the engine.

This method of obtaining IP of the multicylinder engine is known as 'Morse Test'.

1.8 MEASUREMENT OF FUEL CONSUMPTION

Two glass vessels of 100cc and 200cc capacity are connected in between the engine and main fuel tank through two, three-way cocks. When one is supplying the fuel to the engine, the other is being filled. The time for the consumption of 100 or 200cc fuel is measured with the help of stop watch.

A small glass tube is attached to the main fuel tank as shown in figure. When fuel rate is to be measured, the valve is closed so that fuel is consumed from the burette. The time for a known value of fuel consumption can be measured and fuel consumption rate can be calculated.

$$\text{Fuel consumption kg/hr} = \frac{X_{cc} \text{ X Sp. gravity of fuel}}{1000 \text{ x } t}$$

1.9 MEASUREMENT OF HEAT CARRIED AWAY BY COOLING WATER

The heat carried away by cooling water is generally measured by measuring the water flow rate through the cooling jacket and the rise in temperatures of the water during the flow through the engine.

The inlet and out let temperatures of the water are measured by the thermometers inserting in the pockets provided at inlet to and outlet from the engine. The quantity of water flowing is measured by collecting the water in a bucket for a specified period or directly with the help of flow meter in case of large engine. The heat carried away by cooling water is given by

Where $Q_w = C_p m_w (T_{wo} - T_{wi})$ kJ/min.
M_w = mass of water/min.
T_{wi} = Inlet temperature of water, ^oC
T_{wo} = Out let temperature of water, ^oC
C_p = Specific heat of water.

1.10 MEASUREMENT OF HEAT CARRIED AWAY BY EXHAUST GASES

The mass of air supplied per kg of fuel used can be calculated by using the equation if the exhaust analysis is made

$$m_a = \frac{N \, X \, C}{33\,(C_1 + C_2)}$$

And heat carried away by the exhaust gas per kg of fuel supplied can be calculated as

$$Q_g = (m_a + 1)\, C_{pg}\, (T_{ge} - T_a) \text{ kJ/kg of fuel} \qquad \text{....(16)}$$

Where $(m_a + 1)$ = mass of exhaust gases formed per kg of fuel supplied to engine
C_{pg} = Specific heat of exhaust gases
T_{ge} = Temperature of exhaust gases coming out from the engine ^{o}C.
T_a = Ambient temperature ^{o}C or engine room temperature.

The temperature of the exhaust gases is measured with the help of suitable thermometer or thermocouple.

Another method used for measuring the heat carried away by exhaust gases is to measure the fuel supplied per minute and also to measure the air supplied per minute with the help of air box method. The addition of fuel and air mass will be equal to the mass of exhaust gases.

And exhaust gas calorimeter is commonly used in the laboratory for the measurement of heat carried by exhaust gases.

1.10.1Exhaust Gas Calorimeter

The exhaust gas calorimeter is a simple heat exchanger in which, part of the heat of the exhaust gases is transferred to the circulating water. This calorimeter helps to determine the mass of exhaust gases coming out of the engine.

The arrangement of the exhaust gas calorimeter is shown in fig. 23.5.

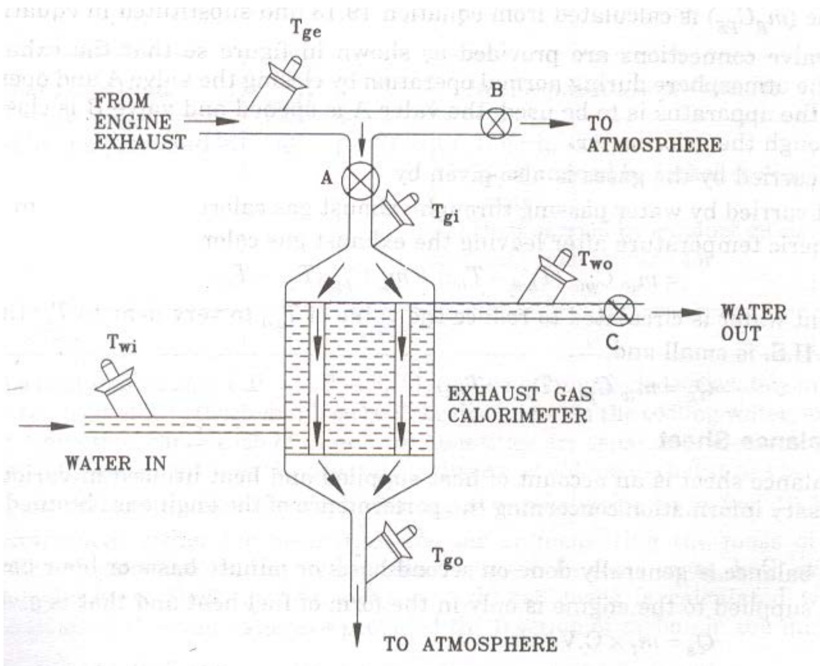


Fig. Exhaust gas calorimeter.

Figure.8

The exhaust gases from the engine exhaust are passed through the exhaust gas calorimeter by closing the valve *B* and opening the valve A. The hot gases are cooled by the water flow rate is adjusted with the help of valve of *'C'* to give a measurable temperature rise to water circulated.

If it is assumed that the calorimeter is well insulated, there is no heat loss except by heat transfer from the exhaust gases to the circulating water, then

Heat lost by exhaust gases = Heat gained by circulating water.

Therefore $m_g, C_{pg} (T_{gi} - T_{go}) = m_w. \ C_{pw} (T_{wo} - T_{wi})$

Where T_{gi} = The temperature of the exhaust gases entering the calorimeter, ^oC

T_{go} = The temperature of the exhaust gases leaving the calorimeter, ^oC

T_{wi} = The temperature of water entering the calorimeter, ^oC

T_{wo} = The temperature of water leaving the calorimeter, ^oC

m_w = Mass of water circulated through the exhaust gas calorimeter, generally measured.

m_g = Mass of exhaust gases (unknown)

C_{pg} = specific heat of exhaust gases.

C_{pw} = Specific heat of water.

$$\therefore m_g = \frac{C_{pw}}{C_{pg}} \left(\frac{T_{wo} - T_{wi}}{T_{gi} - T_{go}} \right) m_w \quad \ldots(17)$$

As all the quantities on the RHS are known the gas flow rate can be determined.

Then the heat carried away by the exhaust gases is given by

$$Q_g = m_g \ C_{pg.} \ (T_{ge} - T_a) \quad \ldots.(18)$$

Where T_{ge} = Temperature of exhaust gases just leaving the engine exhaust valve, ^oC

T_a = Ambient temperature, ^oC

Usually valve connections are provided as shown in figure so that the exhaust gases are exhausted to the atmosphere during normal operation by closing the valve *A* and opening the valve *B*. Only when the apparatus is to be used, the valve *A* is opened and valve *B* is closed so that the gases pass through the calorimeter.

The heat carried by the gases is also given by
Q_g = Heat carried by water passing through exhaust gas calorimeter + Heat in exhaust gases above atmoshpheric temperature after leaving the exhaust gas calorimeter.

$$= m_w C_{pw} (T_{wo} - T_{wi}) + m_g C_{pg} (T_{go} - T_a) \quad \text{...(19)}$$

If sufficient water is circulated to reduce the value of T_{go} to very near to T_a, then the second term on the RHs is small and,

$$Q_g = m_w C_{pw} (T_{wo} - T_{wi}) \quad \text{....(20)}$$

1.11 HEAT BALANCE SHEET

A heat balance sheet is an account of heat supplied and heat utilized in various ways in the system. Necessary information concerning the performance of the engine is obtained from the heat balance.
The heat balance is generally done on second basis or minute basis or hour basis.
The heat supplied to the engine is only in the form of fuel-heat and that is given by

$$Q_s = m_f \text{ X CV}$$

Where mf is the mass of fuel supplied per minute or per sec. and CV is the lower calorific value of the fuel.
The various ways in which heat is used up in the system is given by

(a) Heat equivalent of BP = kW = kJ/sec. = 0 kJ/min.

(b) Heat carried away by cooling water

$$= C_{pw} \text{ X } m_w (T_{wo} - T_{wi}) \text{ kJ/min.}$$

Where mw is the mass of cooling water in kg/min or kg/sec circulated through the cooling jacket and ($T_{wo} - T_{wi}$) is the rise in temperature of the water passing through the cooling jacket of the engine and C_{pw} is the specific heat of water in kJ/kg-K.

(c) Heat carried away by exhaust gases

$$= m_g C_{pg} (T_{ge} - T_a) \text{ (kJ/min.) or (kJ/sec)}$$

Where mg is the mass of exhaust gases in kg/min. or kg/sec and it is calculated by using one of the methods already explained.

T_g = Temperature of burnt gases coming out of the engine.
T_a = Ambient Temperature.
C_{pg} = Sp. Heat of exhaust gases in (kJ/kg-K)

(d) A part of heat is lost by convection and radiation as well as due to the leakage of gases. Part of the power developed inside the engine is also used to run the accessories as lubricating pump, cam shaft and water circulating pump. These cannot be measured precisely and so this is known as unaccounted 'losses'. This unaccounted heat energy is calculated by the different between heat supplied Q_s and the sum of *(a) + (b) (c).*

The results of the above calculations are tabulated in a table and this table is known as "Heat Balance Sheet". It is generally practice to represent the heat distribution as percentage of heat supplied. This is also tabulated in the same heat balance sheet.

Heat input per minute	kcal (kj)	%	Heat expenditure per minute	kcal (kj)	%
Heat supplied by the combustion fuel	Q_s	100%	(a) Heat in BP.	--	--
			(b) Heat carried by jacket cooling water	--	--
			(c) Heat Carried by exhaust gases	--	--
			(d) Heat unaccounted for $= Q_s - (a + b + c)$	--	--
Total	Q_s	100%			100%

A sample tabulation which is known as a heat balance sheet for particular load condition is shown below:

NOTE: The heat in frictional FP (IP – BP) should not be included separately in heat balance sheet because the heat of FP (frictional heat) will be dissipated in the cooling water, exhaust gases and radiation and convection. Since each of these heat quantities are separately measured and heat in FP is a hidden part of these quantities; the separate inclusion would mean that it has been included twice.

The arrangement either for measuring the air or measuring the mass of exhaust gas is sufficient to find the heat carried away by exhaust gases. In some cases, both arrangements are used for cross-checking. Heat carried away by exhaust gases is calculated with the help of volumetric analysis of the exhaust gases provided the fraction of carbon in the fuel used is known.

1.12 . Indicated Specific Fuel Consumption: This is defined as the mass of fuel consumption per hour in order to produce an indicated power of one kilo watt.

Thus, indicated specific fuel consumption = isfc = $\frac{3600\,\dot{m}}{ip}$ kg/kWh …..(13)

1.13.Brake Specific fuel consumption:- This defined as the mass of fuel consumed per hour,
in order to develop a brake power of one kilowatt.

Thus, brake specific fuel consumption = bsfc = $\frac{3600\,\dot{m}}{bp}$ kg/kWh ……..(14)

1.14. Thermal Efficiency : There are two definitions of thermal efficiency as applied to IC engines. One is based on indicated power and the other on brake power.The one based on indicated power is called as *'indicated thermal efficiency"*, and the one based on brake power is known as *"brake thermal efficiency"*.

Indicated thermal efficiency is defined as the ratio of indicated power to the energy available due to combustion of the fuel.

$$\text{Thus } \eta_{ith} = \frac{\text{Indicated Power in kW}}{(\text{Mass flow rate of fuel in kg/s}) \times (\text{Calorific value of fuel in kJ/kg})}$$

$$\text{Or} \quad \eta_{ith} = \frac{ip}{m \times CV} \quad \text{...(15)}$$

Similarly brake thermal efficiency is defined as the ratio of brake power to energy available due to combustion of the fuel.

$$\text{Or} \quad \eta_{bth} = \frac{bp}{m \times CV} \quad \text{...(16)}$$

1.15.Mechanical Efficiency: Mechanical efficiency takes into account the mechanical losses in an engine. The mechanical losses include (i) frictional losses, (ii) power absorbed by engine auxillaries like fuel pump, lubricating oil pump, water circulating pump, magneto and distributor, electric generator for battery charging, radiator fan etc., and (iii) work requited to charge the cylinder with fresh charge and work for discharging the exhaust gases during the exhaust stroke. It is defined as the ratio of brake power to indicated power. Thus

$$\eta_{mech} = \frac{bp}{ip} \quad \text{.................................(17)}$$

1.16. Volumetric efficiency: Volumetric efficiency is the ratio of the actual mass of air drawn into the cylinder during a given period of time to the theoretical mass which should have been drawn in during the same interval of time based on the total piston displacement, and the pressure and temperature of the surrounding atmosphere.

Thus
$$\eta_v = \frac{V_{actual}}{V_{th}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

where n is the number of intake strokes per minute and V_s is the stroke volume of the piston.

2. Illustrative examples:

Example 1:- *The following observations have been made from the test of a four cylinder, two – stroke petrol engine. Diameter of the cylinder = 10 cm; stroke = 15 cm; speed = 1600 rpm; Area of indicator diagram = 5.5 cm^2; Length of the indicator diagram = 55 mm; spring constant = 3.5 bar/cm; Determine the indicated power of the engine.*

Given:- d = 0.1 m; L = 0.15 m ; No. of cylinders = K = 4; N = 1600 rpm; n = N (two – stroke); a = 5.5 cm^2; length of the diagram = l_d = 5.5. cm; spring constant = k_s = 3.5 bar/cm ;
To find: indicated power, ip.

Solution: Indicated mean effective pressure = $p_{im} = \dfrac{a\, k_s}{l_d}$

$$\text{or} \quad p_{im} = \frac{5.5 \times 3.5}{5.5} = 3.5 \text{ bar} = 3.5 \times 10^{5} \text{ N / m}^2$$

$$\text{Indicated power} = ip = \frac{p_{im}\, LAnK}{60{,}000} = \frac{3.5 \times 10^5 \times 0.15 \times (\pi/4) \times 0.1^2 \times 1600 \times 4}{60{,}000}$$

$$= 43.98 \text{ kW}$$

Example 2:- *A gasoline engine (petrol engine) working on Otto cycle consumes 8 litres of petrol per hour and develops 25 kW. The specific gravity of petrol is 0.75 and its calorific value is 44,000 kJ/kg. Determine the indicated thermal efficiency of the engine*

Given:- Volume of fuel consumed/hour = y/t = $8 \times 10^{3} / 3600$ cc/s ;

ip = 25 kW; CV = 44,000 kJ/kg;

Specific gravity of petrol = s = 0.75

To find: η_{ith} ;

Solution: Mass of fuel consumed = $\dot{m} = \dfrac{y\, s}{1000\, t} = \dfrac{8 \times 10^{3} \times 0.75}{1000 \times 3600} = 1.67 \times 10^{-3}$ kg/s.

$$\text{Indicated thermal efficiency} = \eta_{ith} = \frac{ip}{m\, CV} = \frac{25}{1.67 \times 10^{-3} \times 44000}$$

$$= 0.3402 = 34.02\ \%.$$

Example 2.3:- *The bore and stroke of a water cooled, vertical, single-cylinder, four stroke diesel engine are 80 mm and 110 mm respectively.The torque is 23.5 N-m.Calculate the brake mean effective pressure.*
What would be the mean effective pressure and torque if the engine rating is 4 kW at 1500 rpm?

Given:- Diameter = d = 80×10^{-3} = 0.008 m ; stroke = L = 0.110 m; T = 23.5 N-m;

To find (i) bmep ; (ii) bmep if bp = 4 kw and N= 1500 rpm.

Solution: (i) Relation between brake power (bp) and brake mean effective pressure (bmep) is given by

$$bp = \frac{2\pi NT}{60,000} = \frac{(bmep)LAn}{60,000}$$

Hence bmep = (2πNT) / (LAn) = (2πNT) / {(Lπd^2 /4) N/2}

$$= \frac{16T}{d^2L} = \frac{16 \times 23.5}{0.08^2 \times 0.11} = 5.34 \times 10^5 \ N/m^2 = 5.34 \ bar$$

(ii) when bp = 4 kw and N = 1500 rpm, we have

$$bmep = \frac{60,000 \ bp}{LAn} = \frac{60,000 \times 4}{0.110 \times (\pi/4) \times 0.08^2 \times (1500/2)}$$

$$= 5.79 \times 10^5 \ N/m^2 = 5.79 \ bar.$$

Also bp = 2πNT / 60,000 or $T = \frac{60,000 \ bp}{2\pi N} = \frac{60,000 \times 4}{2 \times \pi \times 1500} = 25.46 \ N - m.$

Example 4:-*Find the air fuel ratio of a four stroke, single cylinder, air cooled engine with fuel consumption time for 10 cc is 20.4 s and air consumption time for 0.1 m^{3}is 16.3 s. The load is 7 N at the speed of 3000 rpm. Find also the brake specific fuel consumption in kg/kWh and brake thermal efficiency.Assume the density of air as 1.175 kg/m^3 and specific gravity of the fuel to be 0.7. The lower heating value of the fuel is 43 MJ/kg and the dynamometer constant is 5000.*

Given:- y = 10 cc ; t = 20.4 s ; V_a = 0.1 m^3; t_a = 16.3 s ; W = 7 N ; N = 3000 rpm;

ρ_a = 1.175 kg/m^3; s = 0.7 ; CV = 43 x 10^3 kJ/kg; Dynamometer constant = C = 5000.

To find:- (i) m_a / m_f ; (ii) bsfc ; (iii) $\eta_{bth.}$

Solution: (i) Mass of air consumed = $m_a = \frac{0.1 \times 1.175}{16.3} = 7.21 \times 10^{-3}$ kg/s.

Mass of fuel consumed = $m_f = \frac{y \ s}{1000 \ t} = \frac{10 \times 0.7}{1000 \times 20.4} = 0.343 \times 10^{-3}$ kg/s

$$\text{Air fuel ratio} = \frac{m_a}{m_f} = \frac{7.21 \times 10^{-3}}{0.343 \times 10^{-3}} = 21$$

$$\text{(ii) Brake power} = bp = WN / C = \frac{7 \times 3000}{5000} = 4.2 \text{ kW}$$

$$bsfc = \frac{m_f \times 3600}{bp} = \frac{0.343 \times 10^{-3} \times 3600}{4.2} = 0.294 \text{ kg/kWh}$$

$$\text{(iii) } b_{ith} = \frac{bp}{m_f\, CV} = \frac{4.2}{0.343 \times 10^{-3} \times 43 \times 10^{3}} = 0.2848 = 28.48\ \%.$$

Example 2.5:- *A six cylinder, gasoline engine operates on the four stroke cycle. The bore of each cylinder is 80 mm and the stroke is 100 mm. The clearance volume in each cylinder is 70 cc. At a speed of 4000 rpm and the fuel consumption is 20 kg/h. The torque developed is 150 N-m. Calculate (i) the brake power, (ii) the brake mean effective pressure, (iii) brake thermal efficiency if the calorific value of the fuel is 43000 kJ/kg and (iv) the relative efficiency if the ideal cycle for the engine is Otto cycle.*

Given:- K = 6 ; n = N /2 ; d = 8 cm ; L = 10 cm ; V_c = 70 cc ; N = 4000 rpm ; m_f = 20 kg/h ; T = 150 N-m ; CV = 43000 kJ/kg ;

To find:- (i) bp ; (ii) bmep ; (iii) η_{bth} ; (iv) $\eta_{Relative.}$

Solution:

$$\text{(i) } bp = \frac{2\pi NT}{60{,}000} = \frac{2 \times \pi \times 4000 \times 150}{60{,}000}$$

$$= 62.8 \text{ kW}$$

$$\text{(ii) } bmep = \frac{60{,}000\ bp}{L\ A\ n\ K} = \frac{60{,}000 \times 62.8}{0.1 \times (\pi / 4) \times 0.08^{2} \times (4000/2) \times 6}$$

$$= 6.25 \times 10^{5} \text{ N/m}^2 = 6.25 \text{ bar}$$

$$\text{(iii) } \eta_{bth} = \frac{bp}{m_f\, CV} = \frac{62.8}{(20 / 3600) \times 43{,}000} = 0.263 = 26.3\ \%.$$

(iv) Stroke volume = $V_s = (\pi / 4)\, d^2 L = (\pi / 4) \times 8^2 \times 10 = 502.65$ cc

$$\text{Compression Ratio of the engine} = R_c = \frac{V_s + V_c}{V_c} = \frac{502.65 + 70}{70} = 8.18$$

Air standard efficiency of Otto cycle = $\eta_{Otto} = 1 - (1/ R_c^{\gamma - 1})$

$$= 1 - \frac{1}{8.18^{0.4}} = 0.568 = 56.8\ \%$$

Hence Relative efficiency = $\eta_{Relative} = \eta_{bth} / \eta_{Otto} = 0.263 / 0.568 = 0.463 = 46.3\ \%$.

Example 2.6:- *An eight cylinder, four stroke engine of 9 cm bore, 8 cm stroke and with a compression ratio of 7 is tested at 4500 rpm on a dynamometer which has 54 cm arm. During a 10 minute test, the dynamometer scale beam reading was 42 kg and the engine consumed 4.4 kg of gasoline having a calorific value of 44,000 kJ/kg. Air at 27 C and 1 bar was supplied to the carburetor at a rate of 6 kg/min. Find (i) the brake power, (ii) the brake mean effective pressure, (iii) the brake specific fuel consumption, (iv) the brake specific air consumption, (v) volumetric efficiency , (vi) the brake thermal efficiency and (vii) the air fuel ratio.*

Given:- K = 8 ; Four stroke hence n = N/2 ; d = 0.09 m; L = 0.08 m; $R_c = 7$; N = 4500 rpm; Brake arm = R = 0.54 m ; t = 10 min ; Brake load = W = (42 x 9.81) N

$m_f = 4.4$ kg ; CV = 44,000 kJ/kg ; $T_a = 27 + 273 = 300$ K ; $p_a = 1$ bar; $\dot{m}_a = 6$ kg/min;

To find:- (i) bp ; (ii) bmep ; (iii) bsfc ; (iv) bsac ; (v) η_v ; (vi) η_{bth} ; (vii) $\dot{m}_a / \dot{m}_f$

Solution:

$$\text{(i) bp} = \frac{2\pi NT}{60{,}000} = \frac{2\pi NWR}{60{,}000} = \frac{2 \times \pi \times 4500 \times (42 \times 9.81) \times 0.54}{60{,}000}$$

= 104.8 kW

$$\text{(ii) bmep} = \frac{60{,}000\ bp}{L\ A\ n\ K} = \frac{60{,}000 \times 104.8}{0.08 \times (\pi / 4) \times 0.09^2 \times (4500 / 2) \times 8}$$

$= 6.87 \times 10^5\ N/m^2 = 6.87$ bar.

(iii) mass of fuel consumed per unit time = $\dot{m}_f = m_f / t = 4.4 \times 60 / 10$ kg/h

$= 26.4$ kg/h

$$\text{Brake specific fuel consumption} = bsfc = \frac{\dot{m}_f}{bp} = \frac{26.4}{104.8} = 0.252 \text{ kg / kWh}$$

$$\text{(iv) brake specific air consumption} = bsac = \frac{\dot{m}_a}{bp} = \frac{6 \times 60}{104.8}$$

$= 3.435$ kg / kWh

$$\text{(v) } \eta_{bth} = \frac{bp}{\dot{m}_f \; CV} = \frac{104.8}{(26.4 / 3600) \times 44{,}000} = 0.325 = 32.5\ \%.$$

(vi) Stroke volume per unit time = $\dot{V}_s = (\pi d^2/4)\ L\ n\ K$

$$= \frac{\pi}{4} \times (0.09^2) \times 0.08 \times (4500 / 2) \times 8$$

$= 9.16\ m^3$ / min.

$$\text{Volume flow rate of air per minute} = \dot{V}_a = \frac{\dot{m}_a R_a T_a}{p_a} = \frac{6 \times 286 \times 300}{1 \times 10^5}$$

$= 5.17\ m^3$ / min

Volumetric efficiency = $\eta_v = \dot{V}_a / \dot{V}_s = 5.17 / 9.16 = 0.5644 = 56.44\ \%$.

(vii) Air fuel ratio = $\dot{m}_a / \dot{m}_f = 6 / (4.4 / 10) = 13.64$

Example 2.7:- *A gasoline engine working on four- stroke develops a brake power of 20.9 kW. A Morse test was conducted on this engine and the brake power (kW) obtained when each cylinder was made inoperative by short circuiting the spark plug are 14.9, 14.3, 14.8 and 14.5 respectively. The test was conducted at constant speed. Find the indicated power, mechanical efficiency and brake mean effective pressure when all the cylinders are firing. The bore of the engine is 75mm and the stroke is 90 mm. The engine is running at 3000 rpm.*

Given:- brake power when all cylinders are working = B_t = 20.9 kW ;

Brake power when cylinder 1 is inoperative = B_1 = 14.9 kW ;

Brake power when cylinder 2 is inoperative = B_2 = 14.3 kW ;

Brake power when cylinder 3 is inoperative = B_3 = 14.8 kW ;

Brake power when cylinder 4 is inoperative = B_4 = 14.5 kW ;

N = 3000 rpm ; d = 0.075 m ; L = 0.09 m ;

To find:- (i) $(ip)_{total}$; (ii) η_{mech} ; (iii) bmep ;

Solution:

(i) $(ip)_{total} = ip_1 + ip_2 + ip_3 + ip_4 = (B_t - B_1) + (B_t - B_2) + (B_t - B_3) + (B_t - B_4)$

$= 4B_t - (B_1 + B_2 + B_3 + B_4) = 4 \times 20.9 - (14.9 + 14.3 + 14.8 + 14.5)$

= 25.1 Kw

(ii) $$\eta_{mech} = \frac{B_t}{(ip)_{total}} = \frac{20.9}{25.1} = 0.833 = 83.3\ \%$$

(iii) $$bmep = \frac{60{,}000\ B_t}{L\ A\ n\ K} = \frac{60{,}000 \times 20.9}{0.09 \times (\pi / 4) \times 0.075^2 \times (3000 / 2) \times 4}$$

$= 5.25 \times 10^5\ N / m^2 = 5.25$ bar.

Example 2.8:- *The following observations were recorded during a trail of a four – stroke, single cylinder oil engine.*
Duration of trial = 30 min ; oil consumed = 4 litres ; calorific value of oil = 43 MJ/kg ; specific gravity of fuel = 0.8 ; average area of the indicator diagram = 8.5 cm²; length of the indicator diagram = 8.5 cm; Indicator spring constant = 5.5 bar/cm; brake load = 150 kg; spring balance reading = 20 kg; effective brake wheel diameter = 1.5 m ; speed = 200 rpm ; cylinder diameter = 30 cm ; stroke = 45 cm ; jacket cooling water = 10 kg/min ; temperature rise of cooling water = 36 C. Calculate (i) indicated power, (ii) brake power, (iii) mechanical efficiency, (iv) brake specific fuel consumption, (v) indicated thermal efficiency, and (vi) heat carried away by cooling water.

Given:- t = 30 min ; y = 4000 cc; CV = 43 x10^3 kJ/kg; s = 0.8 ; area of the diagram = a = 8.5 cm^2; length of the diagram = l_d = 8.5 cm ; indicator spring constant = k_s = 5.5 bar / cm; W = 150 x 9.81 N ; Brake radius = R = 1.5 / 2 = 0.75 m; N = 200 rpm ; d = 0.3 m ; L = 0.45 m ; $\dot{m}_w$ = 10 kg/min ; ΔT_w = 36 C; Spring Balance Reading = S = 20 x 9.81 N

To find:- (i) ip ; (ii) bp ; (iii) η_{mech} ; (iv) bsfc ; (v) η_{ith} ; (vi) $\dot{Q}_w$

Solution:

(i) $$p_{im} = \frac{a}{l_d} k_s = \frac{8.5}{8.5} \times 5.5 = 5.5 \text{ bar} = 5.5 \times 10^5 \text{ N/m}^2$$

$$ip = \frac{p_{im} L A n K}{60,000} = \frac{5.5 \times 10^5 \times 0.45 \times (\pi / 4) \times 0.3^2 \times (200/2) \times 1}{60,000}$$

= 29.16 kW

(ii) $$bp = \frac{2\pi N(W - S) R}{60,000} = \frac{2 \times \pi \times 200 \times (150 - 20) \times 9.81 \times 0.75}{60,000}$$

= 20.03 kW

(iii) η_{mech} = bp / ip = 20.03 / 29.16 = 0.687 = 68.7 %.

(iv) Mass of fuel consumed per hour = $$\dot{m}_f = \frac{y\, s}{1000\, t} \times 60 = \frac{4000 \times 0.8}{1000 \times 30} \times 60$$

= 6.4 kg / h.

$$bsfc = \dot{m}_f / bp = \frac{6.4}{20.03} = 0.3195 \text{ kg/kWh}$$

(v) $$\eta_{ith} = \frac{ip}{\dot{m}_f\, CV} = \frac{29.16}{(6.4/3600) \times 43 \times 10^3} = 0.3814 = 38.14\ \%.$$

(vi) $\dot{Q}_w = \dot{m}\, C_p\, \Delta T_w$ = (10 / 60) x 4.2 x 36 = 25.2 kW

Example 2.9:- *A four stroke gas engine has a cylinder diameter of 25 cm and stroke 45 cm. The effective diameter of the brake is 1.6 m.The observations made in a test of the engine were as follows.*

Duration of test = 40 min; Total number of revolutions = 8080 ; Total number of explosions = 3230; Net load on the brake = 80 kg ; mean effective pressure = 5.8 bar; Volume of gas used = 7.5 m^3; Pressure of gas indicated in meter = 136 mm of water (gauge); Atmospheric temperature = 17 C; Calorific value of gas = 19 MJ/ m^3 at NTP; Temperature rise of cooling water = 45 C; Cooling water supplied = 180 kg.

Draw up a heat balance sheet and find the indicated thermal efficiency and brake thermal efficiency. Assume atmospheric pressure to be 760 mm of mercury.

Given:- d = 0.25 m ; L = 0.45 m; R = 1.6 / 2 =0.8 m; t = 40 min ; N_{total} = 8080 ;

Hence N = 8080 / 40 = 202 rpm n_{total} = 3230 ;

Hence n = 3230 / 40 = 80.75 explosions / min; W = 80 x 9.81 N; p_{im} = 5.8 bar ;

V_{total} = 7.5 m^3; hence $\dot{V}$ = 7.5 / 40 = 0.1875 m^3/min; p_{gauge} = 136 mm of water (gauge);

T_{atm} = 17 + 273 = 290 K; $(CV)_{NTP}$ = 19 x 10^3 kJ/ m^3 ; ΔT_w = 45 C;

$\dot{m}_w$ = 180 / 40 = 4.5 kg/min; p_{atm} = 760 mm of mercury

To find:- (i) η_{ith} ; (ii) η_{bth} ; (iii) heat balance sheet

Solution:

(i)
$$ip = \frac{p_{im} L A n K}{60{,}000} = \frac{5.8 \times 10^5 \times (\pi / 4) \times 0.25^2 \times 0.45 \times 80.75}{60{,}000}$$

= 17.25 kW.

$$bp = \frac{2\pi N W R}{60{,}000} = \frac{2 \times \pi \times 202 \times (80 \times 9.81) \times 0.8}{60{,}000}$$

= 13.28 kW

Pressure of gas supplied = p = p_{atm} + p_{gauge} = 760 + 136 / 13.6 = 770 mm of mercury

Volume of gas supplied as measured at NTP = $\dot{V}_{NTP} = \dot{V} (T_{NTP} / T)(p / p_{NTP})$

$$= \frac{0.1875 \times 273 \times 770}{290 \times 760} = 0.17875 \text{ m}^3 / \text{min}$$

Heat supplied by fuel = $\dot{Q}_f = \dot{V}_{NTP}\ (CV)_{NTP} = 0.17875 \times 19 \times 10^3 = 3396.25$ kJ/min

Heat equivalent of bp in kJ/min = 13.28 x 60 = 796.4 kJ/min

Heat lost to cooling water in kJ/min = $\dot{m}_w C_p \Delta T_w = 4.5 \times 4.2 \times 45 = 846.5$ kJ/min

Friction power = ip – bp = 17.25 – 13.28 = 3.97 kW

Hence heat loss due to fiction, pumping etc. = 3.97 x 60 = 238.2 kJ/min

Heat lost in exhaust, radiation etc (by difference) = 3396.25 – (896.4 + 796.4 + 238.2)

= 1465.15 kJ/min

Heat Balance Sheet:

Item No.		*Heat Energy Input (kJ/min)*	*(percent)*	*Heat Energy spent (kJ/min)*	*(percent)*
1	Heat supplied by fuel	3396.25	100.00		
2	Heat equivalent of bp			896.4	26.4
3	Heat lost to cooling Water			796.4	23.4
4	Heat equivalent of fp			238.2	7.0
5	Heat unaccounted (by difference)			1465.15	43.2
	Total	3396.25	100.0	3396.25	100.0

Example 2.10:- *A test on a two-stroke engine gave the following results at full load.*

Speed = 350 rpm; Net brake load = 65 kg ; mean effective pressure = 3 bar ; Fuel consumption = 4 kg/h ; Jacket cooling water flow rate = 500 kg/h ; jacket water temperature at inlet = 20 C ; jacket water temperature at outlet = 40 C ; Test room temperature = 20 C ; Temperature of exhaust gases = 400 C; Air used per kg of fuel = 32 kg ; cylinder diameter = 22 cm ;stroke = 28 cm; effective brake diameter = 1 m ; Calorific value of fuel = 43 MJ/kg ; Mean specific heat of exhaust gases = 1 kJ/kg –K. Find indicated power, brake power and draw up a heat balance for the test in kW and in percentage.

Given:- Two stroke engine. Hence n = N ; N = 350 rpm ; W = (65 x 9.81) N ;

p_{im} = 3 bar ; $\dot{m}_f$ = 4 kg/h ; $\dot{m}_w$ = 500 kg/h ; T_{wi} = 20 C ; T_{wo} = 40 C ; T_{atm} = 20 C ;

T_{eg} = 400 C ; $\dot{m}_a / \dot{m}_f$ = 32 ; d = 0.22 m ; L = 0.28 m ; Brake radius = R = ½ m ;

CV = 43,000 kJ/kg ; $(C_p)_{eg}$ = 1.0 kJ/(kg-K) ;

To find:- (i) ip ; (ii) bp ; and (iii) heat balance;

Solution:

$$\text{(i) ip} = \frac{p_{im}\, LAn}{60{,}000} = \frac{3 \times 10^5 \times 0.28 \times (\pi/4) \times 0.22^2 \times 350}{60{,}000}$$

= 18.63 kW.

$$\text{(ii) bp} = \frac{2\pi\, N\, WR}{60{,}000} = \frac{2 \times \pi \times 350 \times (65 \times 9.81) \times 0.5}{60{,}000}$$

= 11.68 kW.

(iii) Heat supplied in kW = $\dot{m}_f$ CV = (4 / 3600) x 43,000

= 47.8 kW

Heat lost to cooling water = $\dot{m}_w (C_p)_w [T_{wo} - T_{wi}]$

= (500 / 3600) x 4.2 x [40 – 20]

= 11.7 kW.

Heat lost in exhaust gases = $(\dot{m}_a + \dot{m}_f) (C_p)_{eg} [T_{eg} - T_{atm}]$

$$= \frac{(32 + 1) \times 4}{3600} \times 1.0 \times [400 - 20]$$

= 13.9 kW

Heat balance sheet:

Heat Input	kW	%	Heat Expenditure	kW	%
Heat supplied by fuel	47.8	100	Heat in bp	11.68	24.4
			Heat lost to cooling Water	11.70	24.5
			Heat lost to exhaust Gases	13.90	29.1
			Unaccounted heat (by difference)	10.52	22.0
Total	**47.80**	**100**	**Total**	**47.80**	**100.0**