UNIT 5

RATING, TESTING & PERFORMANCE

Course Contents

5.1 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.

Objectives

- With the development of internal combustion and their testing procedures, an Engineer's task is to reduce the cost and increase the power output and the efficiency of the engine. The aims of the engine testing are:
    1. To get the specified information which cannot be possibly determined by calculation.
    2. To justify the rating of the engine and the guaranteed specific fuel consumption.
    3. To verify and confirm the validity of engine data used in designing the engine i.e. to confirm that the actual performance matches with the design specifications.
- The BIS has published IS 14599(1999) as the standard for engine testing for determination of power, specific fuel consumption and smoke capacity (for CI. engine). The Indian standards for measurement of smoke IS 8118 (1998) and IS 14553 (1998) may be referred.

Important performance parameters of ic engine

- Important performance parameters of ic engine are as follow:
    - i. Friction power
    - ii. Indicated power
    - iii. Brake power
    - iv. Fuel consumption
    - v. Air flow
    - vi. Speed
    - vii. Exhaust and coolant temperature
    - viii. Emissions
    - ix. Noise

5.2 IS Standard Code 10000 to 10004 for Testing of Engines

- IS standard code 10000 (Part I to Part XI) to 10004 specifies the Indian standards for testing of vehicles.

Table 5. 1 IS Standard Code

IS Code		Details
IS : 10000	Part I	Glossary of terms related to test methods
	Part II	Standard reference conditions
	Part III	Measurements for testing, units and limit of accuracy
	Part IV	Declarations of power, efficiency specific fuel consumption and lubricating oil consumption

	Part V	Preparation for tests and measurement for wear
	Part VI	Recording of test results
	Part VII	Governing test for constant speed engines. Also, the selection of engine for use with electrical generators.
	Part VIII	Performance test
	Part IX	Endurance test procedures both for constant speed and variable speed engines. It is performed after tests specified in part VIII Endurance test for constant speed engines is carried and for 32 cycles in which each cycle is of 16 hrs continuous running. Before start of next cycle the temperature of oil sump is brought down to within 5°C of its initial temperature. Endurance test for variable speed engines is conducted for 10 cycles (100 hrs) in which each cycle is of 10 hrs with interval of 2 hrs between cycles 10 hrs duration is divided into 5 cycles of each 2 hr duration. Results obtained are corrected to standard reference conditions and compared to results of part VI above.
	Part X	Test for smoke levels for variable speed engines.
IS 10000	Part XI	Information supplied by manufacturer test certificates
IS : 10001		Deals with specification for performance requirements for constant speed diesel engines up to 20 kW capacity.
IS : 10002		Same as above but for engines above 20 kW capacity
IS : 10003		Deals with specification for performance requirement of variable speed diesel engine for automotive purposes.
IS : 10004		Specifications for performance requirement for variable speed spark ignition (S.L) engines for automotive purposes.

5.3 Indicated Power (I.P.)

- The indicated power of an engine is the power developed within the cylinder. In order to determine the indicated power it is necessary to plot (p-V) diagram representing the actual conditions of the engine within the cylinder since the area of (p-V) diagram gives the work developed by the engine per cycle.
- Knowing the speed and type of engine the rate of work developed can be evaluated.
- The apparatus used for drawing actual (p-V) diagram is called engine indicator shown in Fig. 5.1.
- In order to estimate the indicated power of an engine the following methods are usually followed.
  1. Using the indicator diagram
  2. By adding two measured quantities viz. brake power and friction power
  3. From morse test

- Engine indicator consists of a cylinder, piston and piston rod. On the cylinder a coupling nut is fitted.
- The coupling nut is connected to a gas hole tap which is fitted to the cylinder head of the engine to be tested.

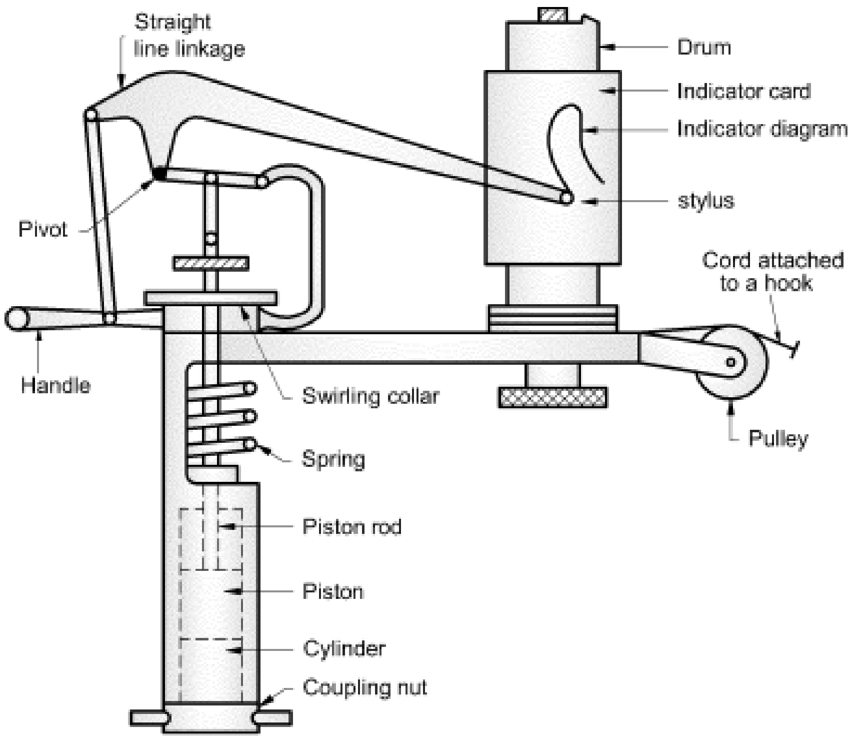


Fig. 5. 1 Engine indicator (Mechanical type)

- The gas tap connects through passages both to the cylinder of indicator and to the combustion chamber of the engine cylinder.
- The piston slides in the cylinder and the piston rod is connected to straight line linkage through a spring of proper stiffness.
- The straight line linkage is mounted on a swinging collar which can rotate on the top of the indicator cylinder.
- The spring controls the movement of the piston according to the pressure of engine cylinder.
- A stylus (pencil) is attached at the end of straight line linkage so that it moves in a vertical line in proportion to the movement of piston by magnifying its movement.
- A drum, to which a paper or indicator card can be fixed, is mounted on a vertical spring and shaft. It is rotated by a cord wound round it, the other end of which is attached to a point on the engine whose motion is same as that the piston of the engine cylinder.
- The vertical movement of the stylus and the horizontal movement of the cord combines to produce a closed figure known as indicator diagram.
- The area enclosed on the indicator diagram measures the work developed during a stroke to a definite scale.
- It should be noted that the stiffness of the spring is chosen appropriate to the maximum pressure in the cylinder.
- These type of indicators are not suitable for measurement in case of high speed engines due to its mechanical nature. Usually, these are found suitable up to a speed of 1500 r.p.m.

Indicated Mean Effective Pressure (I.M.E.P.)

- It represents that constant pressure which if it is acted over the full length of the stroke would produce the same amount of work done by the piston as is actually produced by the engine cylinder during a cycle.

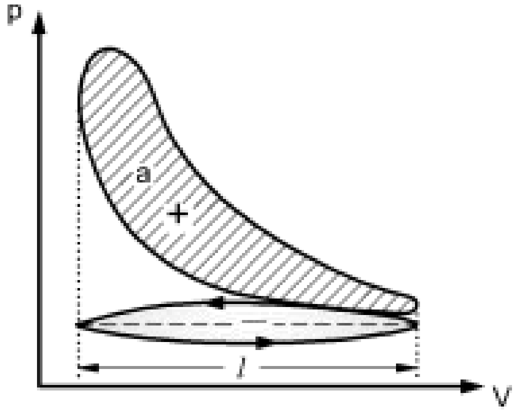


Fig. 5. 2 Indicator diagram

- i.m.e.p. can be determined with the help of indicator diagram shown in Fig. 2.2. The area of indicator diagram can be measured with the help of planimeter.

Let, a = Net area of indicator diagram (cm^2)
l = Length of indicator diagram (cm)
K = Spring constant, N/cm^2 /cm

Therefore,

$$Mean\ height\ of\ diagram = \frac{a}{l}$$

$$i.m.e.p. = \frac{a}{l} \times K\ (N/cm^2)$$

Indicated power (I.P.):

Let, p_m = Indicated mean effective pressure (N/cm^2)

$$\mathrm{A} = \text{Cross} - \text{sectional area of piston } (\mathrm{cm}^2) = \frac{\pi}{4}(d)^2$$

Where,

d = Diameter of piston or bore (cm)
L = Length of stroke (m)
n = Number of power strokes per minute
N = Speed of the engine (r.p.m.)
n = Power stroke /min
= N/2 for 4 S engine as one power stroke per 2 rev &
= N for 2S engine

$$\text{Force on piston} = \mathrm{p}_m \times \mathrm{A}\ (\text{Newtons})$$

$$\text{Work done per cycle} = (\mathrm{p}_m \times \mathrm{A})\ \mathrm{L}\ (\mathrm{Nm})$$

$$I.P. = p_m \, A \, Ln \; (Nm / min)$$

$$I.P. = p_m \, A \, L \frac{n}{60} \; (Nm/s \;\; or \, W)$$

$$I.P. = \frac{p_m \, A \, Ln}{60000} \; (kW)$$

5.4 Measurement of Brake Power (B.P.)

- Measurement of brake power is an important test carried out in the test schedule of an engine.
- It involves the determination of the torque and the angular speed of the engine output shaft. The torque measuring device is called a dynamometer.

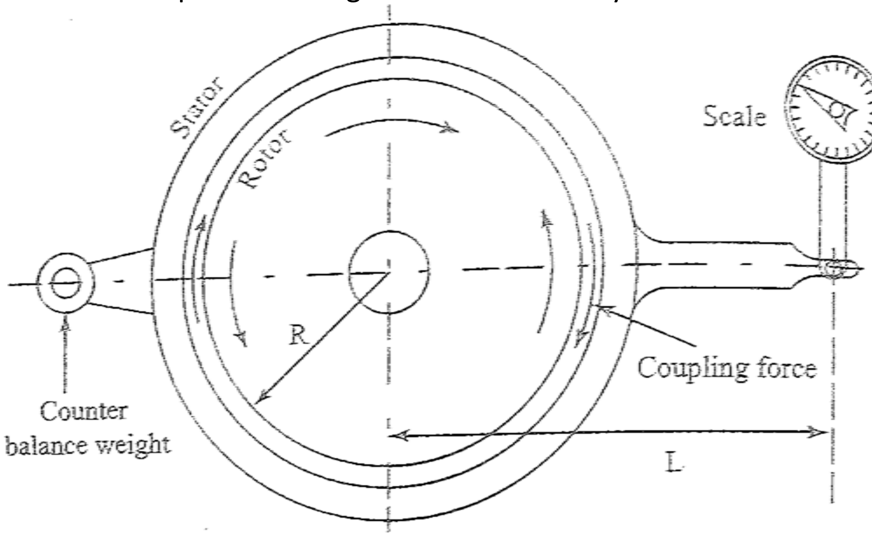


Fig. 5. 2 Principle of a dynamometer

- Figure shows the basic principle of a dynamometer. A rotor driven by the engine under test, is mechanically, hydraulically or electromagnetically coupled to a stator. For every revolution of the shaft, the rotor periphery moves through a distance $2\pi R$ against the coupling force, F. Hence the work done per revolution is

$$W = 2\pi RF$$

- The external moment or torque is equal to S x L , where S is the scale reading and L is the arm length. This moment balances the turning moment R x F, i.e.,

$$S \times L = R \times F$$

Therefore

$$\text{Work done/revolution} = 2\pi SL$$

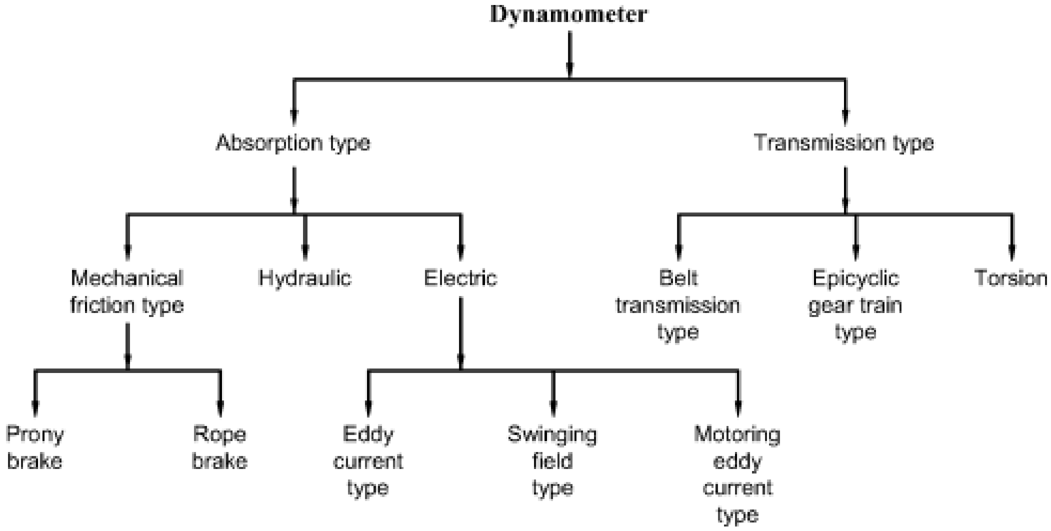
$$\text{Work done/minute} = 2\pi SLN$$

- Hence brake power is given by

$$bp = 2\pi NT \; Watts$$

Where, T is the torque and N is rpm.

Classification of dynamometers



1. Prony Brake Dynamometer:

– One of the simplest methods of measuring power output of an engine is to attempt to stop the engine by means of a mechanical brake on the flywheel and measure the weight which an arm attached to the brake will support, as it tries to rotate with the flywheel. This system is known as the prony brake and from its use, the expression brake power has come. The prony brake consists of a frame with two brake shoes gripping the flywheel

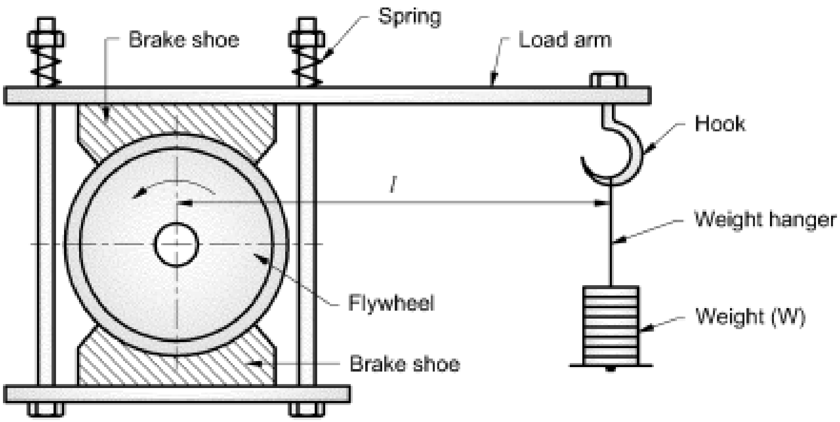


Fig. 5. 3 Prony Brake Dynamometer

– The pressure of the brake shoes on the fly wheel can be varied by the spring loaded using nuts on the top of the frame. The wooden block when pressed into contact with the rotating drum opposes the engine torque and the power is dissipated in overcoming frictional resistance. The power absorbed is converted into heat and hence this type of dynamometer must be cooled.

Let, W = Weight on hanger (N)
L = Distance from centre to flywheel to the hanger called load arm (m)
N = Speed (rpm)

Torque = W × L

$$B.P = \frac{(W \times L)2\pi N}{\quad} kW$$

2. Rope brake Dynamometer:

- The rope brake as shown in Fig. is another simple device for measuring *bp* of an engine. It consists of a number of turns of rope wound around the rotating drum attached to the output shaft.
- One side of the rope is connected to a spring balance and the other to a loading device. The power absorbed is due to friction between the rope and the drum. The drum therefore requires cooling.

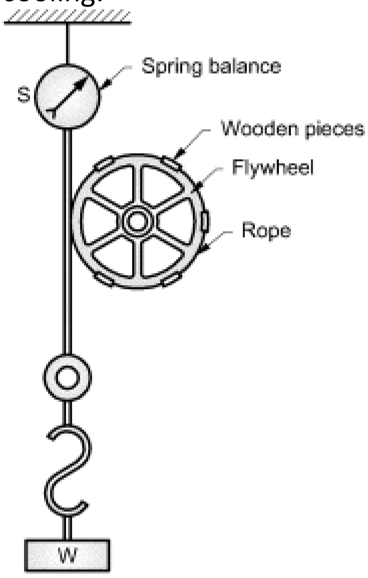


Fig. 5. 4 Rope Brake Dynamometer

- Rope brake is quite cheaper and can be easily fabricated but not very accurate because of changes in the friction coefficient of the rope with temperature.

Let, W = Dead weight (Newtons)

S = Spring balance reading (Newtons)

$$\text{Rb} = \text{Radius of brake drum or flywheel (effective)} = \frac{D+d}{2}$$

Where, D = Brake drum diameter, and

d = Rope diameter

N = Speed in r.p.m.

Brake load or net load = (W – S)

Braking torque = (W – S) Rb

$$Brake\ Power = \frac{(W-S)R_b \times 2\pi N}{60000} kW$$

- With the help of brake power, the brake mean effective pressure (b.m.e.p.) can be calculated from the following equation,

$$Brake\ Power = \frac{(bmep)ALn}{60000} = \frac{(P_{mb})ALn}{60000} kW$$

3. Hydraulic Dynamometer:

- The hydraulic dynamometer was developed by Froude in 1877. This dynamometer is useful for measuring brake power over wide range of power and speeds.
- These are accurate, simple in construction, and free from vibration and

– Fig. shows the part of a hydraulic dynamometer. It consists of a shaft supported in shaft bearings. The casing is carried by the anti-friction trunions so that it is free to swirl about the same axis as the axis of the shaft.
– The shaft carries a rotor in the form of semi-elliptical cross-section divided one from another by means of oblique vanes.
– The internal faces of the casing are provided with liners which are pocketed in the same way.

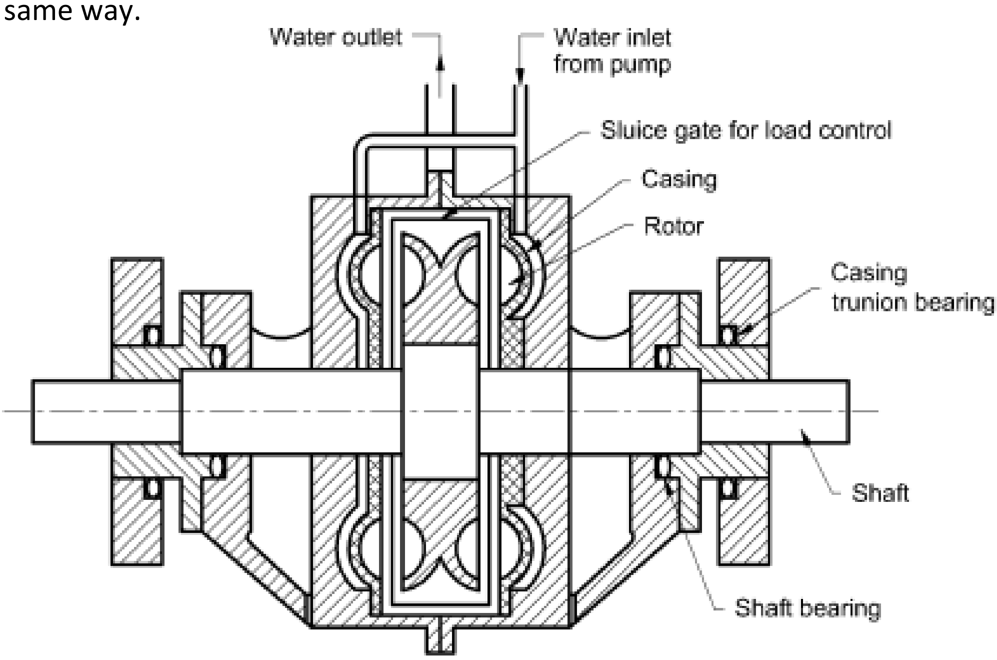


Fig. 5. 5 Hydraulic Dynamometer

– The pockets in rotor and liners together form an elliptical receptacles round which the water runs across at high speed.
– The engine shaft is directly coupled to dynamometer shaft. The water is circulated to the rotor to provide the hydraulic resistance and it carries away the heat developed due to absorption of power by water.
– The water is discharged from the rotor at high speed from its periphery into pockets formed in by the casing liners, by which it is then returned at diminished speed into rotor pockets near the shaft.
– The output can be controlled by controlling the sluice gates which can be moved in and out partially or fully to obstruct the flow of water between the rotor and casing.
– The resistance offered to motion of rotor reacts on the casing which tends to turn on its antifriction roller supports. This tendency is countered by means of a lever arm carrying weight 'W' which measures the torque.

$$Brake\ Power = \frac{W.N}{K}$$

Where, W = weight on lever arm (N)
N = speed (r.p.m.)
K = dynamometer constant

4. Swinging Field Dynamometer:

- This type of dynamometer is usually used to measure brake power of high speed engines. It consists of an electric generator with its field system mounted on the trunions.
- The casing of the generator can revolve due to unbalancing of the applied and reactive torques.
- The torque supplied to the field of the dynamometer and the reaction of the electromagnetic induction on frame causes it to revolve about its shaft.
- This is counterbalanced by applying the external dead load or by the spring force.
- The speed of rotation is measured.
- The product of the applied external load, the load arm and the speed will give the power transmitted.

5. Eddy Current Dynamometer:

- Fig. represents the principle of working of an eddy current dynamometer. It consists of a rotor disc made of steel or copper. The rotor shaft is supported in the bearings and it is coupled to the engine shaft.
- Its stator is fitted with a number of electromagnets and the stator cradles in the trunion bearing.
- When the rotor rotates, it produces the eddy currents in the stator due to magnetic flux set up by the passage of field current in the electromagnets.

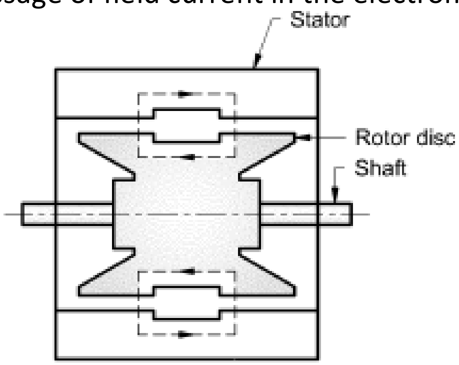


Fig. 5. 6 Eddy current dynamometer

- These eddy currents oppose the rotor motion, thus loading the engine.
- The torque is measured with the help of torque arm and the load as in the other types of dynamometers explained above.
- This dynamometer also requires to be provided with some cooling arrangement since the produced eddy currents are dissipated in producing heat.

Advantages of eddy current dynamometer:

1. It can measure high power output at all speeds therefore, these are suitable to test automobile and aircraft engines.
2. Its size is small compared to other dynamometers.
3. The torque developed is smooth and continuous under all operating conditions.
4. These dynamometers can be produced in all sizes for measurement of power.

6. Transmission Dynamometer

- Transmission dynamometers, also called torque meters, mostly consist of a set of strain gauges fixed on the rotating shaft and the torque is measured by the angular deformation of the shaft which is indicated as strain of the strain gauge. Usually a four-arm bridge is used to reduce the effect of temperature to minimum and the gauges are arranged in pairs such that the effect of axial or transverse load on the strain gauges is avoided.
- Figure shows a transmission dynamometer which employs beams and strain-gauges for a sensing torque.

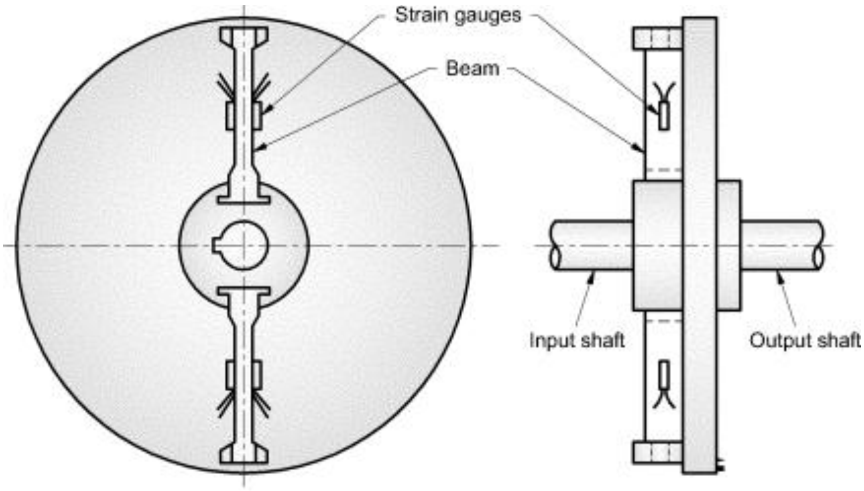


Fig. 5. 7 Transmission dynamometers

- Transmission dynamometers are very accurate and are used where continuous transmission of load is necessary. These are used mainly in automatic units.

5.5 Friction power

- The difference between the indicated and the brake power of an engine is known as friction power. The internal losses in an engine are essentially of two kinds, viz., pumping losses and friction losses. During the inlet and exhaust stroke the gaseous pressure on the piston is greater on its forward side (on the underside during the inlet and on the upper side during the exhaust stroke), hence during both strokes the piston must be moved against a gaseous pressure and this causes the so called pumping loss.
- The friction loss is made up of the friction between the piston and cylinder walls, piston rings and cylinder walls, and between the crankshaft and camshaft and their bearings, as well as by the loss incurred by driving the essential accessories, such as the water pump, ignition unit etc.
- It should be the aim of the designer to have minimum loss of power in friction. Friction power is used for the evaluation of indicated power and mechanical efficiency. Following methods are used to find the friction power to estimate the performance of the engine.

  1. Willan's line method
  2. Morse test
  3. Motoring test
  4. From the measurement of indicated and brake power
  5. Retardation test

1. Willan's line method

– In Willan's line method, gross fuel consumption vs. BP at a constant speed is plotted and the graph is extrapolated back to zero fuel consumption as illustrated in Figure. The point where this graph cuts the BP axis in an indication of the friction power of the engine at that speed. This negative work represents the combined loss due to mechanical friction, pumping and blow by.
– In petrol engine, we keep the air-fuel mixture constant and vary the amount of the mixture intake for required torque or power. This is called quantitative governing. In diesel engine, we draw a constant volume of air (compressed) and vary the fuel injected. Technically, we alter the quality of the air - fuel mixture, this is called qualitative governing.
– In SI engine, at low speeds, the air mixture intake is very low (quantitative governing). Hence, there will be a low pressure region created inside the cylinder due to which, there will be pumping losses. Therefore, there will be more friction power than actual, we get erroneous output if we use Willan's line test for SI engine.
– If we use the same test for CI engines, there is qualitative governing and hence, there will be fixed amount of air entering the cylinder and no negative pressure and pumping losses occurs. So, we get a relatively closer value of friction power, the errors are greatly minimized.
– So, Willan's line method is applicable only to Diesel (C.I) engines.

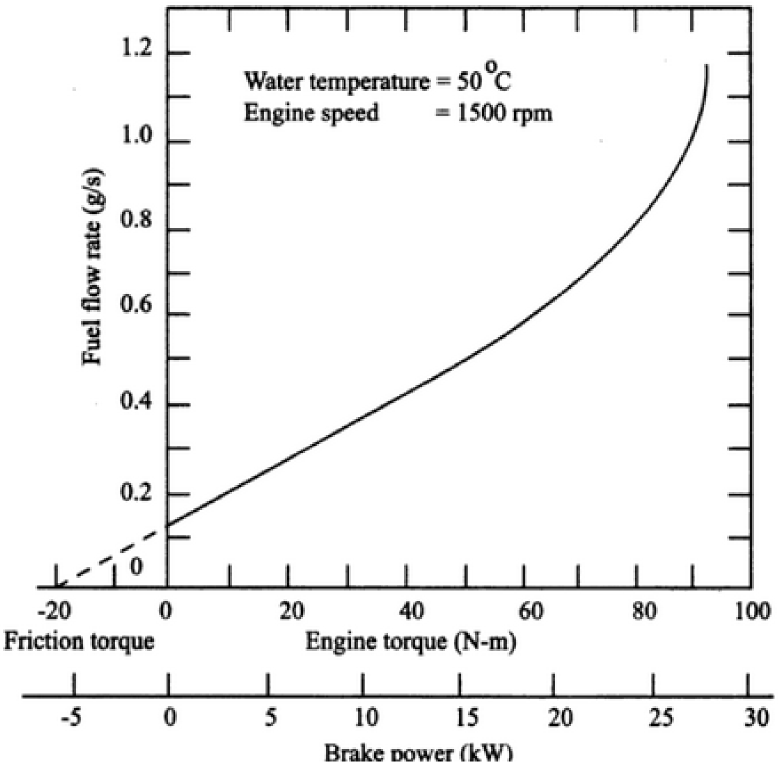


Fig. 5. 8 Willan's line method

– The main drawback of this method is the long distance to be extrapolated from data measured between 5 and 40% load towards the zero line of fuel input.
1. The directional margin of error is rather wide because of the graph which may not be a straight line many times.

2. The changing slope along the curve indicates part efficiencies of increments of fuel. The pronounced change in the slope of this line near full load reflects the limiting influence of the air-fuel ratio and of the quality of combustion.
3. Similarly, there is a slight curvature at light loads. This is perhaps due to difficulty in injecting accurately and consistently very small quantities of fuel per cycle.
4. Therefore, it is essential that great care should be taken at light loads to establish the true nature of the curve.
5. The Willan's line for a swirl-chamber CI engine is straighter than that for a direct injection type engine.
6. The accuracy obtained in this method is good and compares favorably with other methods if extrapolation is carefully done.

2. Morse test

- The indicated power (ip) of multi cylinder engine can be found out by this method, is not possible to find ip for single cylinder that is the limitation of this method. Also, in the method the indicator or indicator diagram is not required. For multi cylinder engine, power developed in any one cylinder is cut off and output power (bp) is measured. In case of petrol (S.I.) engines, each cylinder in turn is rendered inoperative by shorting the spark plug of the cylinder and in case of diesel (C.I.) engines by cutting off the fuel supply to cylinders successively.
- Consider a four cylinder spark ignition engine coupled to a dynamometer. Throughout the test the engine is run at constant speed of N r.p.m. It is assumed that the pumping and mechanical friction losses are the same whether the cylinder is working or not. Also, the throttle position is kept constant throughout the test.
- Let :

  B = B.P. of the engine when all the four cylinders are working
  B_1 = B.P. of the engine when cylinder - 1 is cut - off
  B_2 = B.P. of the engine when the cylinder - 2 is cut-off
  B_3 = B.P. of the engine when cylinder - 3 is cut-off
  B_4 = B.P. of the engine when cylinder - 4 is cut-off.

  I_1, I_2, I_3 and I_4 be the indicated power (I.P.) developed by cylinder numbers 1, 2, 3 and 4 respectively and their corresponding friction power (F.P) be F_1, F_2, F_3 and F_4.

  Total brake power (B) = $(I_1 + I_2 + I_3 + I_4) - (F_1 + F_2 + F_3 + F_4)$
  $B_1 = (I_2 + I_3 + I_4) - (F_1 + F_2 + F_3 + F_4)$
  On subtracting Equation
  $B - B_1 = I_1$
  Similarly, we could write the equations when the other cylinders are cut-off in turn as follows:
  $B - B_2 = I_2$
  $B - B_3 = I_3$
  $B - B_4 = I_4$
  On adding Equations
  Total indicated power, $I = I_1 + I_2 + I_3 + I_4 = 4B - (B_1 + B_2 + B_3 + B_4)$
  Frictional power, $F = I - B$
  F.P. = I.P. – B.P

Errors involved in measurement of F.P. by Morse Test:

- Though the measurement of frictional power is fairly accurate, however, the errors involved in measurement of F.P. by this method are :

1. In petrol engines using common intake manifolds may affect the distribution of mixture and the volumetric efficiency of each cylinder.
2. The use of common exhaust manifolds and the cutting off the cylinders may cause pulsations in the exhaust system, which in turn will affect the performance of the engine.

3. Motoring Test:

- In motoring test method of determining the frictional power, the engine is run up to its rated power till steady state conditions are reached. The power developed by engine is absorbed by a swinging field dynamometer connected to engine shaft. Either the ignition of a petrol engine or the fuel supply of a diesel engine, as the case may be, is then cut-off.
- By suitable changes in electric switching devices, the dynamometer is run as a motor at the same speed at which the engine was run.
- The output of the motor is measured which would represent the frictional power losses of the engine. In order to maintain the operating temperatures of the engine, the cooling water system is also cut-off during the motoring test.
- Errors involved in measurement of F.P. by motoring test:
- However, the motoring test does not give the true friction losses at the test speed and load for the following reasons :
    1. Temperatures during the motoring test are lower than those in a firing engine due to cooling by the incoming air and heat transfer to the surroundings.
    2. Reduced temperatures reduces the lubricating oil temperatures and increases oil viscosity, therefore, it increases friction power.
    3. The pressure and load on bearings and piston rings are lower than firing engine, it reduces frictional power.
    4. The clearance between piston and cylinder is more due to reduced temperatures in the cylinder. It reduces the friction losses.
    5. Friction power is also affected due to air being drawn at a temperature lower than firing engine since it is not heated from cylinder walls.
    6. Back pressure is more than the firing engine since after expansion, the required pressure difference is not available to impart kinetic energy to expel the exhaust gases.
- However, motoring test gives fairly good results since the increased and reduced friction losses almost balance each other.
- This method is very useful for finding the friction losses caused by various components by progressively stripping off the engine component for research purposes.

4. From the Measurement of Indicated and Brake Power

- This is an ideal method by which fp is obtained by computing the difference between indicated power obtained from an indicator diagram and brake power obtained by a dynamometer. This method is mostly used only in research laboratories as it is necessary to have elaborate equipment to obtain accurate indicator diagrams at high speeds.

5. Retardation Test

- This test involves the method of retarding the engine by cutting the fuel supply. The engine is made to run at no load and rated speed taking into all usual precautions. When the engine is running under steady operating conditions the supply of fuel is cut-off and simultaneously the time of fall in speeds by say 20%, 40%, 60%, 80% of the rated speed is recorded. The tests are repeated once again with 50% load on the engine. The values are usually tabulated in an appropriate table. A graph connecting time for fall in speed (x-axis) and speed (y-axis) at no load as well as 50% load conditions is drawn as shown in Fig.

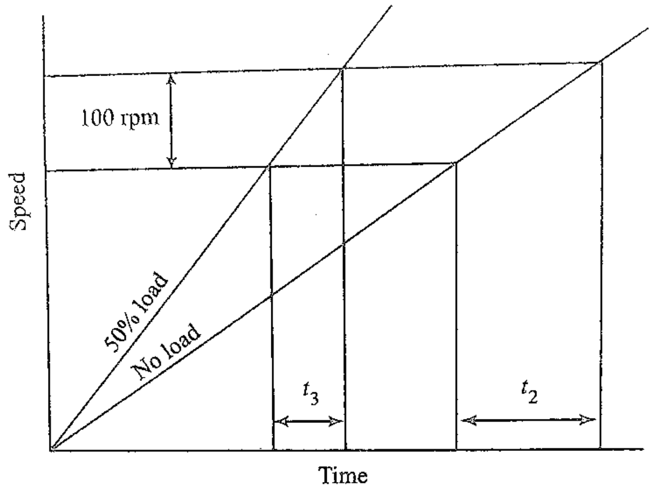


Fig. 9. 9 Graph for Retardation Test

- From the graph the time required to fall through the same range (say 100 rpm) in both, no load and load conditions are found. Let t_2 and t_3 be the time of fall at no load and load conditions respectively. The frictional torque and hence frictional power are calculated as shown below. Moment of inertia of the rotating parts is constant throughout the test.

$$Torque = Moment\ of\ Inertia\ \times Angular\ Accelaration$$

- Let ω be the angular velocity and $\frac{d\omega}{dt}$ be the angular acceleration.

$$T = I\,\frac{d\omega}{dt}$$

$$But, I = MK^2$$

$$\therefore\ T = MK^2\frac{d\omega}{dt}$$

$$d\omega = \frac{T}{MK^2}dt$$

- Now integrating between the limits ω_1 and ω_2 for time t_1 and t_2 ,

$$\int_{\omega_1}^{\omega_2} d\omega = \frac{T}{MK^2}\int_{t_1}^{t_2} dt$$

$$\therefore (\omega_2 - \omega_1) = \frac{T}{MK^2} (t_2 - t_1)$$

- Let T_f be the friction torque and T_l the load torque. At no load the torque is only friction torque T_f and at load the torque is $T_f + T_l$. Hence at no load

$$\therefore (\omega_2 - \omega_1) = \frac{T_f}{MK^2} (t_2 - 0)$$

- The reference angular velocity ω0 is that at, say 1000 rpm, the time of fall for the same range at load

$$\therefore (\omega_0 - \omega_1) = \frac{T_f + T_l}{MK^2} (t_3 - 0)$$

$$(T_f + T_l)t_3 = T_f t_2$$

$$\frac{t_2}{t_3} = \frac{(T_f + T_l)}{T_f} = 1 + \frac{T_l}{T_f}$$

$$\frac{T_l}{T_f} = \frac{t_2}{t_3} - 1 = \frac{t_2 - t_3}{t_3}$$

$$\therefore T_f = T_l \left(\frac{t_3}{t_2 - t_3} \right)$$

- T_l is the load torque which can be measured from the loading t_2 and t_3 are observed values. From the above T_f can be calculated and there by the friction power.

Comparison of Various Methods

- The Willan's line method and Morse tests are comparatively easy to conduct. However, both these tests give only an overall idea of the losses whereas motoring test gives a very good insight into the various causes of losses and is a much more powerful tool.
- As far as accuracy is concern, the ip – bp method in the most accurate, if carefully done. Motoring methods usually gives a higher value for fp as compared to that given by the Willan's line method. Retardation method, though simple, require, accurate determination of the load torque and the time for the fall in speed for the same range.

5.6 Fuel Measurement

- Fuel consumption of an engine may be expressed either in terms of volume or mass of fuel supplied in a specified time. The two basic types of fuel measurement are :
  i. Volumetric type flow meters
  ii. Gravimetric type flow meters

1. Volumetric Type Fuel Flow meter:

- A simple arrangement for measurement of fuel supply in laboratory is shown in Fig. It consists of two spherical shells of 100 cc and 200 cc capacity.

- These are connected to two-three way cocks so that one spherical shell feeds the engine while the other is filled from the fuel tank.
- The time required to feed the given volume of fuel is noted.

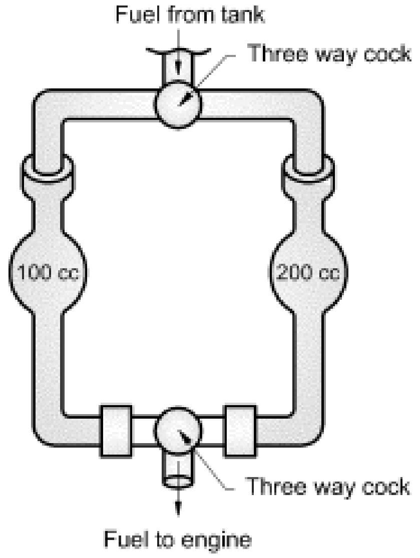


Fig.5.10 Volumetric Type Fuel Flow meter

- The mass flow rate of fuels supply is,

$$m_f = \frac{Volume}{Time} \times Density\ of\ fuel$$

- Where, density of fuel ρ_f = Specific gravity of fuel $\times$density of water ρ_w

  (But, ρ_w = 1000 kg / m^3)

- The disadvantage of this method is that it does not give exact mass flow rate due to variation in density with temperature.

2. Gravimetric Fuel Flow meter:

- Fig. shows the arrangement for direct measurement of the mass of fuel supplied.
- When the measurement of fuel supply is not required, the valve B is closed and the valve A is kept open so that the fuel from fuel tank is directly supplied to the engine.
- When the measurement of fuel flow is required, both the valves A and B are kept open. The quantity of fuel in flask is weighed on the balance.
- After this the valve A is closed and the valve B is kept open so that the fuel from flask flows into engine and the time is measured.
- The quantity of fuel in the flask is again weighed. In this way the mass flow rate of fuel supplied to the engine can be determined.

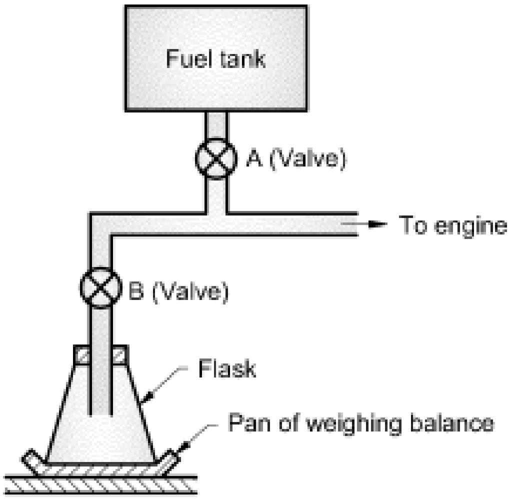


Fig. 5. 11 Direct weighing of fuel flow

5.7 Measurement of Air Consumption

1. Air Flow Meter:

- The air flow meter is shown in Fig. for measurement of air consumption in a laboratory. It consists of a surge tank of capacity (400-600) times to the displacement volume of the engine so as to reduce pulsations. The surge tank is connected to the intake side of the engine with an orifice of cross-sectional area A and of known coefficient of discharge Cd.
- The pressure difference causing the air flow is measured with the help of a water manometer.
- Let $(\Delta H)_w$ be the pressure difference measured in cm of water and $(\Delta H)_{air}$ the corresponding pressure difference in cm of air. Based on unit area of manometer, the head in terms of meters of air is given by,

$$(\Delta p) = (\Delta H)_w \times 1 \times \rho_w = (\Delta H)_{air} \times 1 \times \rho_{air}$$

$$(\Delta H)_{air} = \frac{\rho_w}{\rho_{air}} \times (\Delta H)_w$$

  where , $\rho_w = 1000 \text{ kg / m}^3$

- The volume flow rate of air is given by,

$$V = C_d \times A \times \sqrt{2g(\Delta H)_{air}}$$

$$V = C_d \times A \times \sqrt{2g\frac{\rho_w}{\rho_{air}} \times (\Delta H)_w}$$

$$m_{air} = V.\rho_a$$

$$m_{air} = C_d \times A \times \sqrt{2g.\rho_w.\rho_a(\Delta H)_w}$$

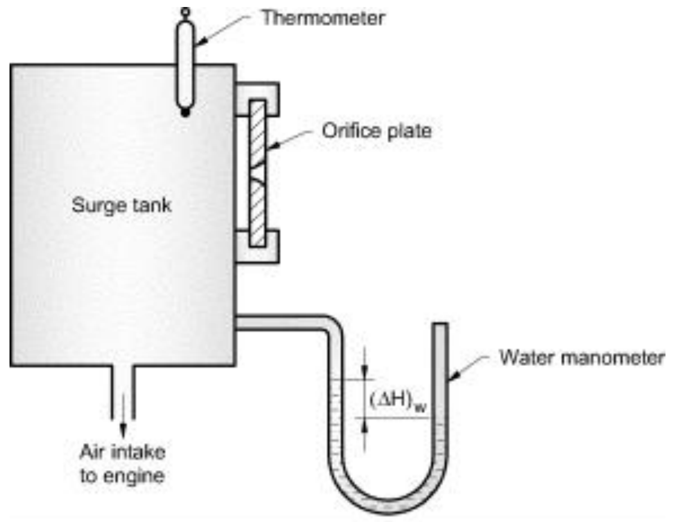


Fig. 5. 12 Air flow meter

2. Viscous Air Flow Meter:

- For accurate measurement of air flow, Alcock viscous air flow meter is shown in Fig.
- This meter uses an element where viscous resistance is the principal source of pressure loss with negligible kinetic effects. Therefore, it gives a linear relationship between the flow and the pressure drop.
- The air is passed through the air filter so as to remove any contamination in it.
- The air now passes over the viscous element consisting of very large number of passages in the form of honeycomb; each passage being triangular size (0.5 mm × 0.5 mm × 75 mm approx.)
- The pressure drop is measured with the help of a manometer.
- Felt pads are fitted in the manometer connections to damp out fluctuations.

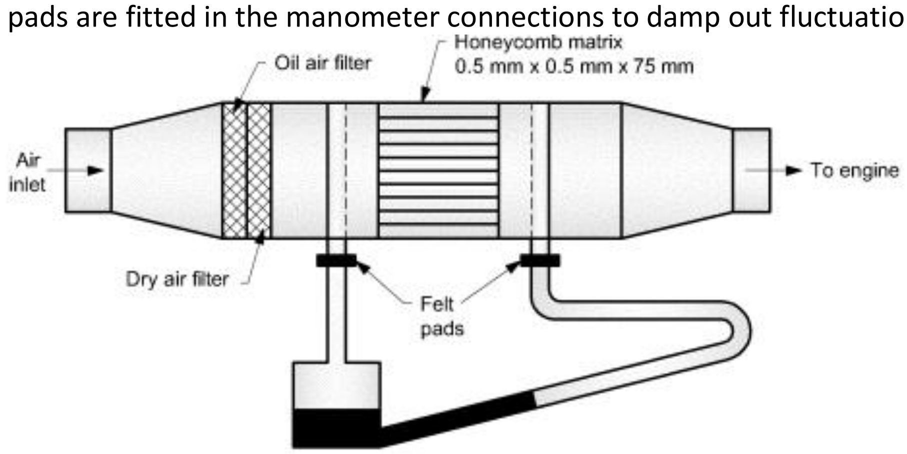


Fig. 5. 13 Alcock viscous air flow meter

5.8 Measurement of Speed

- The speed of the engine can be measured with the help of techometers (mechanical or electrical), mechanical counters and timers, stroboscope, electronic pulse counters etc. However, mechanical and electrical techometers are affected by the temperature variation and they are not very accurate.
- For accurate and continuous measurement of speed a magnetic pick up placed near a toothed wheel coupled to the engine shaft can be used. The magnetic pick up will

produce a pulse every revolution and a pulse counter will measure the speed accurately.

5.9 Heat Balance Sheet or Energy Balance

- Heat balance sheet represents an account of the heat supplied in fuel and released in combustion and its utilization in the engine. Necessary information concerning the performance of the engine is obtained from the heat balance sheet.
- In order to draw a heat balance sheet, a complete test on the engine must be carried out while the engine is run at constant load.
- Heat supplied: Energy is supplied to the engine in the form of fuel supplied to the engine, its heat being released during combustion.

$$Heat\ supplied = m_f \times C.V.(kJ/min)$$

Where, m_f = mass flow rate of fuel (kg/min)

C.V. = Calorific value of fuel in kJ/kg

Heat expenditure / Heat utilised:

- Heat energy of the fuel is partly converted into useful work equivalent to its B.P. and the remainder is carried away by cooling water, exhaust gases and some of heat is lost in radiation, incomplete combustion, lubricating oil, which remains unaccounted for.

Note: Frictional power is not accounted in the heat calculations since friction work is converted into heat which in turn is transferred partly to cooling water and remainder is carried away by exhaust gases.

Calculations for expenditure of heat are as follows:

a) Heat equivalent to B.P.:

- Heat equivalent to brake power per min = B.P. × 60 (kJ/min)

b) Heat rejected to cooling water:

- Heat carried away by cooling water per minute

$$= m_w \times C_{pw} \times (t_{wo} - t_{wi})$$

Where, m_w=mass of cooling water circulated in kg/min

C_{pw} = specific heat of water = 4.187 kJ/kg K

t_{wi} = cooling water inlet temperature (°C)

t_{wo} = cooling water outlet temperature (°C)

Heat carried away by exhaust gases:

- Heat carried away by exhaust gases per minute

$$= m_g \times C_{pg} \times (t_g - t_o)$$

Where, m_g=mass flow of flue or exhaust gases (kg/min)

m_g=mass flow rate of air m_a + mass flow rate of fuel m_f

C_{pg} = specific heat of gases

t_g = temperature of exhaust gases (°C)

t_0 = room temperature (°C) or surrounding temperature

Heat balance sheet

Table 5. 2 Heat balance sheet

Heat supplied	kJ/min	%	Heat Expenditure	kJ/min	%
Heat supplied by Combustion of fuel $= \dot{m}_f \times C.V.$	–	100	(a) Heat in B.P. = B.P. × 60	–	–
			(b) Heat rejected to cooling water $= \dot{m}_w \times C_{pw} \times (t_{c2} - t_{c1})$	–	–
			(c) Heat carried away by exhaust gases $= \dot{m}_g \times C_{pg} \times (t_g - t_0)$	–	–
			(d) Heat unaccounted due to radiation etc. (by difference)	–	–
Total	–	100%	Total	–	100%

5.10 Variables Affecting Engine Performance

– Important variables which affect the engine performance are as follows:

1. Compression ratio:

– The increase in compression ratio increases the thermal efficiency of the engine. However, increased C.R. ratio increases the pressure and temperature which results into higher friction losses of the engine.

– Moreover, increased C.R. tends to increase detonation in S.I. engines. Thus the C.R. is limited to a certain value for better performance.

2. Air-fuel ratio:

– Lean mixtures are used for economic running of the engine while the stoichiometric air-fuel ratios are used for development of maximum power and during acceleration of the engine.

3. Rate of combustion and ignition timing:

– In case of S.I. engines the igniting timings are adjusted to provide the combustion rates such that the maximum pressure occurs to the beginning of power stroke i.e. at T.D.C. for smooth running of the engine.

– In case of C.I. engines, the fuel injection is so timed that it provides the half of total pressure rise during combustion almost near to TDC. For optimum performance.

4. Engine speed:

– Increase in speed of the engine, increases the mass flow rate of air. It increases the power output. However, the increased speeds also increase the friction losses.

– Thus the optimum of the engine should be adjusted so as to provide the optimum performance.

5. Mass of intake charge and supercharging of engines:

– Higher the mass flow rates will provide better volumetric efficiency and power output. Mass flow rates can be improved by supercharging the engine.

- But in case of S.I. engines, the supercharging is not employed due to increased tendency of detonation whereas of supercharged C.I. engines run smooth.

5.11 Methods of Improving Engine Performance

- Basically, the engine performance can be improved either by increasing the energy input to the engine or by improving the conversion efficiency of engine, following methods are suggested to improve the engine performance:
  1. By increasing mass flow rate of mixture.
  2. Supercharging the engine.
  3. Use of larger piston diameters.
  4. Use of fuels of higher calorific value.
  5. Increased engine speeds.
  6. By improving its volumetric efficiency by reducing pressure losses in intake manifolds and reducing the mixture flow restrictions.
  7. Use of higher compression ratios.
  8. Use of fuel additives, exhaust gas recirculation, positive crankcase ventilation etc.
  9. Reduction in heat losses.

5.12 Performance Characteristics of an Engine

- Engine Performance Characteristics are the Graphical Representation of Engine Performance.
- Laboratory tests are performed to determine I.P., B.P., mechanical efficiency, thermal efficiency and specific fuel consumption. The performance characteristics of S.I. and C.I. engines are being discussed below.

1. S.I. Engines:

- Fig. 9.14 (a), (b) and (c) represent the performance characteristic curves for a variable speed S.I. engine.
- At full load the throttle is kept wide open and the speed is varied by adjusting the brake load.
- The I.P., B.P. and fuel consumptions are measured as discussed earlier. Similar tests can be carried out at half load by changing the brake load to half of full load at the same speed.
- It can be observed that the I.P. increases when i.m.e.p or the speed or both of them increase.
- The I.P. increases first with the increase in speed if the inlet conditions are kept constant.
- However, after certain limit the rate of increase of I.P. is reduced with increase in speed because of drop in pressure at intake and reduction in volumetric efficiency.
- Mechanical losses increase with increase in speed due to which the increase in I.P. is offset by the increased losses; therefore, the mechanical efficiency reduces with increase in speed as shown in Fig. (b).

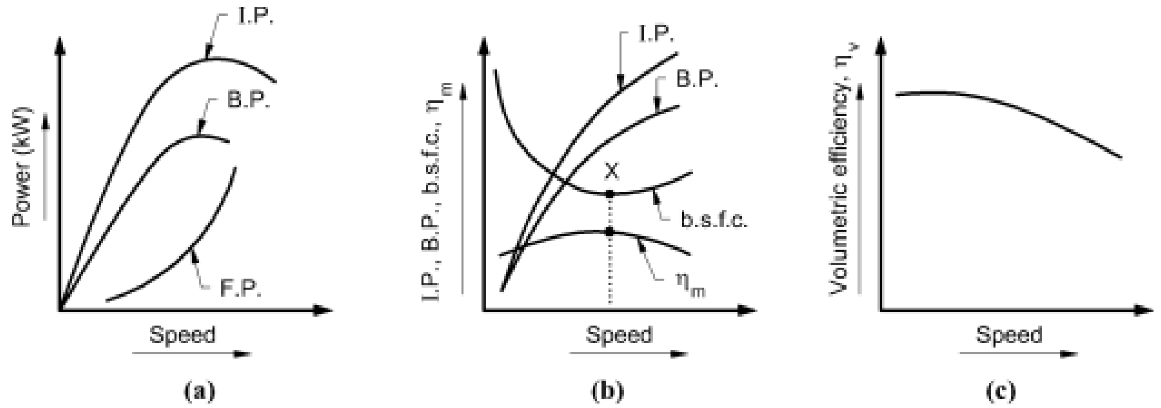


Fig. 5. 14 Performance curve for S.I. engine

- The effect on brake specific fuel consumption (b.s.f.c.) with variation in speed is also represented in Fig. (b). At low speeds with increase in speed the b.s.f.c. reduces since the volumetric efficiency and mechanical efficiency are high.
- After certain speed the b.s.f.c. increases because of reduction in volumetric efficiency and increased mechanical losses.
- Point-X represents the economical speed for minimum fuel consumption for the engine.
- Fig.(c) shows the variation of volumetric efficiency with speed. The volumetric efficiency reduces with the increase in speed because of drop in pressure at suction caused by increase in velocity of charge to be inducted.
- The suction valve will only open when pressure inside the cylinder is slightly below the surrounding pressure, thus the effective suction stroke is reduced.
- It reduces the volume of mixture inducted lowering the volumetric efficiency.

2. C.I. Engines:

- Fig. 9.15 shows the performance curves for C.I.engine at various speeds.
- Fig. 9.15 shows the variation of brake fuel consumption Vs B.P. for S.I. and C.I. engines when run at constant speed.
- The test is carried out by keeping the speed constant and by varying the throttling from no load to maximum load in case of S.I. engines or by varying the fuel supply in case of C.I. engines.

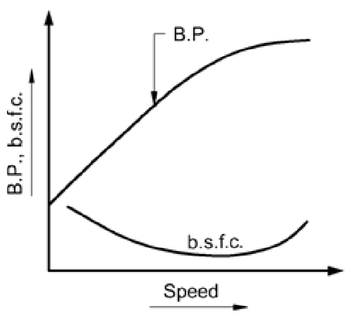


Fig. 5. 15 Performance curve for CI engine

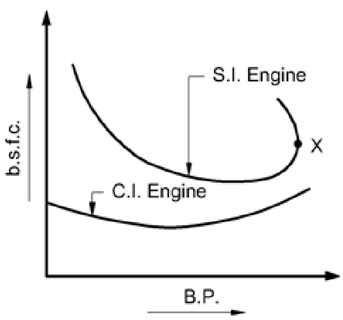


Fig. 5. 16 Performance curve for SI and CI engine at constant speed

- It could be seen that in case of S.I. engines the b.s.f.c. first decreases with increase in load while working at part loads upto a certain minimum value and then it starts increasing rapidly with further increase in loads.

- Beyond full load the curve starts forming a loop backward beyond point - X which shows that the output decreases but the fuel consumption increases. It is due to the fact that the mixture supplied to the engine is too rich and lot goes as unburnt in the exhaust.
- Such a condition of the engine is called choking. In case of C.I. engines the b.s.f.c. Vs B.P. curve is more uniform and the specific fuel consumption is lower than S.I. engines.

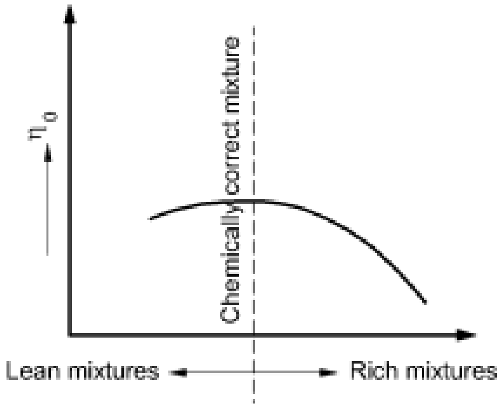
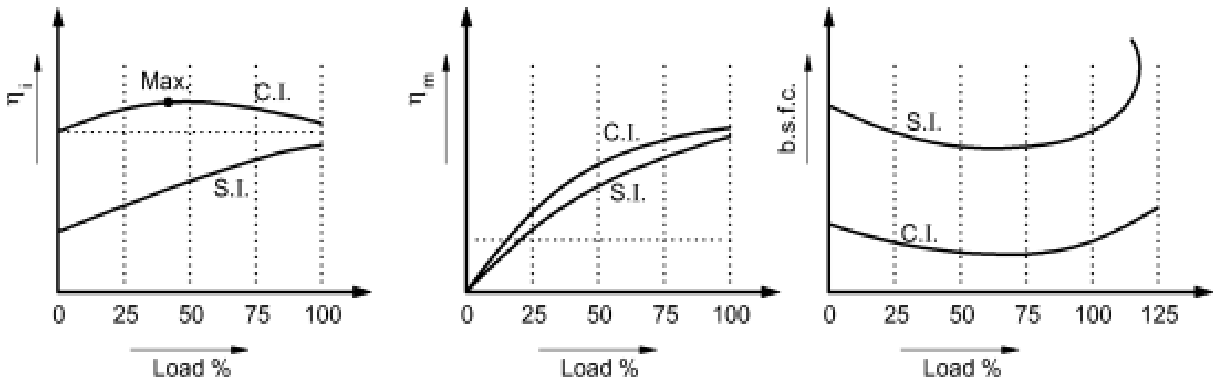


Fig. 5. 17 Brake thermal Vs Mixture strength

- It shows that the thermal efficiency of C.I. engine is higher than that of the S.I. engine and the specific fuel consumption in case of C.I. engines is not much affected with variation in load on the engine.
- Fig. 9.20 shows the performance curve between brake or overall thermal efficiency (η_o) and mixture strength.
- It shows that with slightly weak mixtures the thermal efficiency is maximum since the fuel supplied will be utilised to maximum extent.
- While the efficiency is low with very lean mixtures because of lower maximum temperatures attained after combustion and also the efficiency is low with rich mixtures due to incomplete combustion of fuel.

3. Effect of Load on Different Engine Parameters:

- The engine speed of an engine is maintained constant with the help of governor and the load on the engine is varied. The variation of indicated thermal efficiency, mechanical efficiency and brake specific fuel consumption vs percentage of load on the engine is shown in Fig. 9.18(a), 9.18(b) and 9.18(c) respectively.



(a) η_i vs load *(b) η_m vs load* *(c) b.s.f.c. vs load*

– The conclusions are as follows :

a) Indicated thermal efficiency:

– The indicated thermal efficiency increases with the increase in load for S. I. engines. While for C. I. engines, the indicated thermal efficiency first increases to maximum at about 40% of load and then decreases with increase in load as shown in Fig. 9.21(a).

b) Mechanical efficiency:

– Referring to Fig. 9.21(b), it is observed that the mechanical efficiency increases with load for both type of engines. Since friction power is less than the rate in increase in B. P. of the engine.

– Mechanical efficiency of C. I. engine is more than the mechanical efficiency of S. I. engine at the same load since friction losses in C. I. engines are less compared to S. I. engines.

c) Brake specific fuel consumption:

– Referring to Fig. 9.21(c), it is observed that the b.s.f.c. reduces with load upto 70% to 80% of load since combustion is efficient but with further increase in load, the b.s.f.c. reduces since at higher loads the friction losses increase considerably. While in case of C. I. engines, the b.s.f.c. keeps on reducing upto 90% load.

4. Comparison of Performance of S. I. and C. I. Engines:

– It should be noted that higher indicated mean effective pressure results into higher power developed for a given displacement. The comparison between S.I. and C.I. engines is given below.

Table 5. 3 Comparison

Sr. No.	Aspect	S.I. Engine	C.I. Engine
(i)	Power output/unit weight	High	Low, since the base of high C.R. makes the engine heavy.
(ii)	Acceleration	High due to low inertia	Low due to high inertia
(iii)	Power output/unit displacement	Low due to low C.R.	High due to high C.R

5. Performance Maps:

– Major variables to evaluate the performance of an engine are :

i. Engine speed
ii. Brake power (B.P.) or load
iii. Piston speed
iv. Specific fuel consumption

– Therefore for the critical analysis of an I.C. engine under all conditions of load and speed, a set of curves can be drawn which are independent of the size of engine. Such a map of curves is called the performance map.

– These performance maps can be used to predict the performance of geometrically similar engines because the performance parameters are used in generalized form by converting rotational speed (N) into piston speed and power output as power output per unit area of the piston.

- The performance map of a S.I. engine is shown in Fig. 9.19.

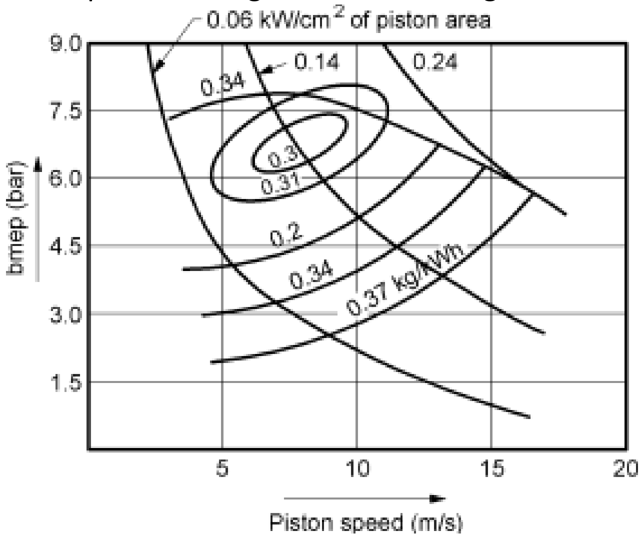


Fig. 5. 19 Performance map of a S.I. engine

- The minimum consumption in kg/kWh shows the point of maximum efficiency. It could be seen from the map, it occurs at low piston speeds with high bmep.
- It is evident that b.s.f.c increases with decrease in bmep because of the reduced mechanical efficiency at low loads since the frictional mean effective pressure almost remains the same.
- Fig. 9.20 shows the performance map for a C.I. engine.

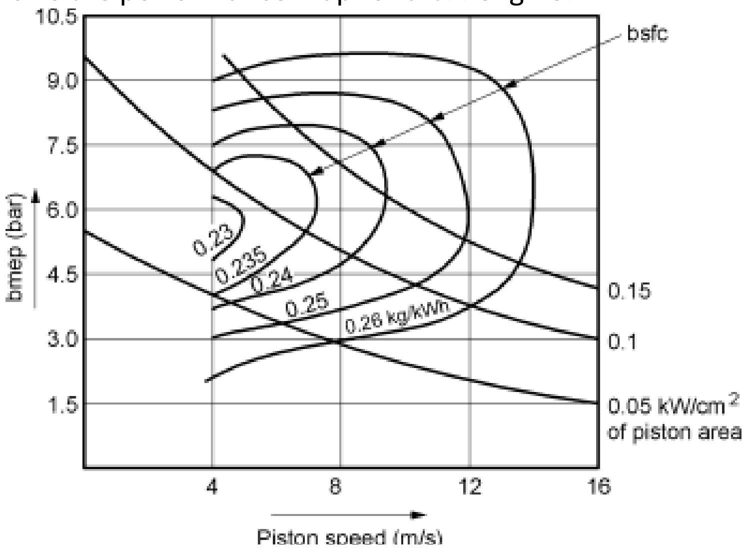


Fig. 5. 20 Performance map of a C.I. engine

- Following observations can be made:
  i. b.s.f.c increases with increase in bmep (i.e. due to increase in load). It is due to the fact that low A.F. ratio at high loads causes increased unburnt carbon. Whereas, the b.s.f.c also increases at low loads because of the decreased mechanical efficiency.
  ii. Minimum b.s.f.c is attained at almost half the maximum bmep i.e. corresponding to its maximum power.

5.13 Variable compression ratio (VCR) engine

- One of the successful methods of improving the specific output of the engine is the use of VCR engine. It can solve the problem of high peak pressures by reducing the compression ratio (C.R.) at full loads by allowing the turbocharger to boost the intake pressures and thus increasing the specific output. While at low and part loads the specific power output can be increased by use of high compression ratios.

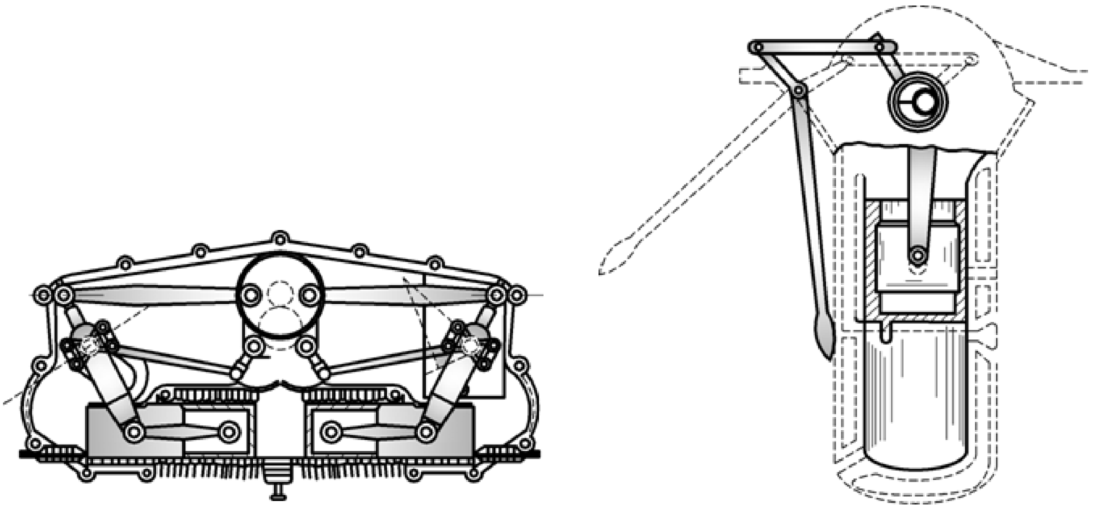
- *Therefore, a VCR engine can improve the specific power output by use of low C.R. at full loads and by use of high C.R. at part loads without facing the problem of peak pressures.*
- The concept of VCR engine can be used both for S.I. and C.I. engines. But this concept is more suitable for C.I. engines since,
  i. The part load efficiency of a C.I. engine is higher than S.I. engine and the concept of VCR is beneficial at part loads only.
  ii. Diesel engines have better multi fuel capabilities.
  iii. It is believed that the variable C.R. may cause detonation problems in case of S.I. engines in a short period of time.

1. Methods of Obtaining Variable Compression Ratio:

- Variable compression ratio in an engine can be obtained by the following methods:
  1. By changing the clearance volume. In this method the compression ratio is changed by lowering or raising the piston crown.
  2. By changing both the clearance volume and the stroke length. This method requires a variable throw crankshaft for changing the stroke length.

Various mechanisms for VCR engines are:

i. Fig. 9.21(a) shows a mechanism in which the stroke length is changed according to load on the engine. Such a mechanism being too complex, this method is not generally adopted in practice.



(a) *(b)*

Fig. 5. 21 (a) VCR engine by changing the stroke length
(b) Variman VCR engine using movement of crank shaft

ii. Fig. 9.21(b) shows a mechanism for variable compression ratio as developed by Tecquiment Ltd. (U.K.) which uses the movement of the crankshaft for varying the compression ratio in the range or 4.5: 1 to 20: 1.

- In this system, the crankshaft and the main bearing assembly is carried in a cradle having two forged transverse members, its ends are connected by hollow pins on each side of the crankshaft and in parallel direction to it.

– The cradle swings about one of the pivot formed by these pins and the other pivot is used for adjustment. The adjustment rod has an eye at its lower end carrying the hollow pin and its upper end is threaded to take a nut in the form of a worm wheel.
– In case the worm wheel is rotated, the crankshaft and its main bearings move up and down thus charging the clearance volume and thus affecting the compression ratio as mentioned above.

iii. The most promising VCR mechanism is as adopted and developed by British Internal Combustion Engine Research Institute (BICERI) as shown in Fig. 9.22. The mechanism uses a special piston to lower or raise the piston skirt.

– The mechanism consists of two main parts A and B called shell and carrier respectively. The carrier B is mounted on the gudgeon pin and the shell A slides on the carrier B. The movement of the shell causes the change in clearance volume, hence changes the compression ratio.
– Parts A and B form two chambers C and D which are kept full by lubricating oil supplied through the hole provided in the connecting rod and a non-return valve F from the lubricating system.

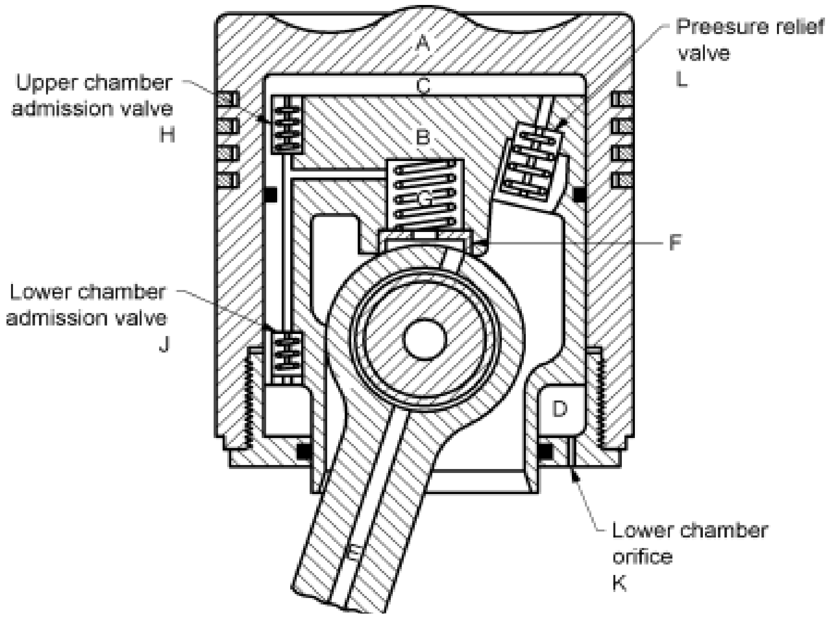


Fig. 5. 22 VCR engines developed by BICERI

– The gas loads on the piston is carried by the lubricating oil in the chamber C. This gas pressure increases with the increase in load on the engine. When gas pressure exceeds the designed value, the spring loaded relief valve L opens and discharges oil to the main sump. The piston shell A will slide down upto a position decided by the relationship between the oil pressure in two chambers and the cylinder gas pressure. Therefore, this movement of the shell will affect the change in C.R. of the engine.

2. Performance of VCR Engine:

1. Power output

– When VCR and fixed C.R. engines were tested of the same size at same speed it was observed that :
   i. b.m.e.p. and power output is high.
   ii. b.s.f.c. remains the same.

iii. Weight to power ratio reduces considerably.

2. Thermal loads

– With VCR engine as per the load on the engine, the duration of heat released is decreased. It leads to smooth combustion both at low and high compression ratios.
– The low C.R. at high loads provides the following advantages :
  i. Reduction in combustion chamber temperatures.
  ii. Maximum pressure decreases and the ignition lag increases.
  iii. Volumetric efficiency increases.
– Above points leads to overall decrease in thermal loads in VCR engines.

3. S.f.c.

– The reduced compression ratio at high loads decreases the thermal efficiency of the engine with increase in specific fuel consumption (sfc). However, these effects are counter balanced by the following factors.
  i. F.P. remains constant irrespective of loads against the increased F.P. in case of fixed C.R. engines with increase in loads on the engine.
  ii. Lower rate of expansion permits the better combustion of fuel because of availability of sufficient time for combustion.

4. Engine noise

– Noise from engines depend on the peak pressure in the cylinder and the rate of pressure rise. The peak pressures affect the lower frequency noise and the rate of pressure rise affects the high frequency noise. Therefore, VCR engines are more silent compared to fixed C.R. engines since the VCR engines have lower peak pressures which remain constant irrespective of the load on the engine.

5. Cold starting and idling

– Since VCR engine works at high compression ratio at low loads, it has very good starting and idling performance at low ambient temperatures.

6. Multifuel capability

– It has good Multifuel capability particularly in case of opposed piston engine type engine since it operates at higher C.R. at low and part loads.

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