TESTING AND PERFORMANCE

18.1 INTRODUCTION

The basic task of the development engineer is to reduce the cost and improve power output and reliability of the engine. In trying to achieve these goals he has to try various design concepts. To find the effects on engine performance of a particular design concept he has to resort to testing. Thus, in general, a development engineer will have to conduct a wide variety of engine tests starting from simple fuel and air-flow measurements to taking of complicated injector needle lift diagrams, swirl patterns and photographs of the burning process in the combustion chamber. The nature and the type of the tests to be conducted will depend upon a great number of factors, some of which are: the degree of development of the particular design, the accuracy required, the funds available, the nature of the manufacturing company, and its design strategy. It is beyond the scope of this book to discuss all of them. In this chapter only certain basic tests and measurements will be considered.

18.2 PERFORMANCE PARAMETER

Engine performance is an indication of the degree of success with which it is doing its assigned job, *i.e.* the conversion of the chemical energy contained in the fuel into the useful mechanical work. The degree of success is compared on the basis of the following:

(i) Specific fuel consumption.
(ii) Brake mean effective pressure.
(iii) Specific power output.
(iv) Specific weight

(v) **Exhaust smoke and other emissions.**

The particular application of the engine decides the relative importance of these performance parameters. For example, for an aircraft engine specific weight is more important whereas for an industrial engine specific fuel consumption is more important.

However, in the evaluation of engine performance certain basic parameters are chosen and the effect of various operating conditions, design concepts and modifications on these parameters are studied. The basic performance parameters are following:

1. Power and mechanical efficiency.
2. Mean effective pressure and torque.
3. Specific output.
4. Volumetric efficiency.
5. Fuel-air ratio.
6. Specific fuel consumption.
7. Thermal efficiency and heat balance.
8. Exhaust smoke and other emissions.
9. Specific weight.

1. **Power and mechanical efficiency.** The main purpose of running an engine is mechanical power. Power is defined as the rate of doing work and is equal to the product of force and linear velocity or the product of torque and angular velocity. Thus, the measurement of power involves the measurement of force (or torque) as well as speed. The first is done with the help of a dynamometer and the latter by a tachometer or by some other suitable device.

The power developed by an engine at the output shaft is called the *brake power* (b.p.) and is given by

$$\text{b.p.} = 2\pi NT \tag{18.1}$$

where T is torque in Nm and N is the rotational speed in revolutions per second

$$T = WR \tag{18.2}$$

where $W = 9.81 \times$ net mass (in kg) applied (18.3)
R = radius in m

The total power/developed by combustion of fuel in the combustion chamber is, however, more than the b.p. and is called *indicated power* (i.p.). Of the power developed by the engine, *i.e.* i.p., some is consumed in overcoming friction between moving parts, some in the process of inducting the air and exhausting the products of combustion from the engine combustion chamber.

Indicated power is the power developed in the cylinder and thus, forms the basis of evaluation of *combustion efficiency* or the heat release in the cylinder.

The difference between the i.p. and b.p. is the indication of the power lost in the mechanical components of the engine and forms the basis of *mechanical efficiency*; which is defined as follows:

Mechanical efficiency = b.p./i.p. (18.4)

The difference between i.p. and b.p. is called *friction power (f.p.)*.

$$\text{f.p.} = \text{i.p.} - \text{b.p.} \tag{18.5}$$

$\therefore$ Mechanical efficiency = b.p./(b.p. + f.p.) (18.6)

2. **Mean effective pressure and torque.** Mean effective pressure, p_m, is defined as a hypothetical pressure which is thought to be acting on the piston throughout the power stroke.

$$p_m = \frac{\text{net area of indicator diagram in mm}^2}{\text{length of indicator diagram in mm} \times \text{spring constant}} \tag{18.7}$$

Indicated power per cylinder, i.p. = $p_{im}\,ALN/n$ watts (18.8)

where
p_{im} = indicated mean effective pressure, N/m^2
L = length of the stroke, m
A = area of the piston, m^2
N = rotational speed of the engine, rev/s
n = number of revolutions required to complete one engine cycle
(n = 1 for two-stroke engine,
n = 2 for four-stroke engine)

Thus

For 4-stroke engine, i.p./cylinder $= p_{im} \cdot A \cdot L \cdot \frac{N}{2}$

For 2-stroke engine, i.p./cylinder $= p_{im} \cdot A \cdot L \cdot N$

For hit and miss governing, i.p./cylinder
$= p_{im} \cdot A \cdot L \cdot \times$ Number of working strokes per sec

Thus, we see that for a given engine the power output can be measured in terms of mean effective pressure. If the mean effective pressure is based on b.p. it is called the *brake mean effective pressure* (bmep), and if based on i.p. it is called *indicated mean effective pressure* (imep). Similarly, the *friction mean effective pressure* (fmep) can be defined as

$$\text{fmep} = \text{imep} - \text{bmep} \tag{18.9}$$

The torque is related to mean effective pressure by the relation

$$\text{b.p.} = 2\pi N T \tag{18.10}$$

By equation (18.8), $2\pi N T = \dfrac{p_{bm} A L N}{n}$

where p_{bm} = brake mean effective pressure

or $$T = \frac{p_{bm} A L}{n} \times \frac{1}{2\pi} \tag{18.11}$$

Thus the torque and the mean effective pressure are related by the engine size. A larger engine produces more torque for the same mean effective pressure. For this reason, torque is not the measure of the ability of an engine to utilize its displacement for producing power from fuel. It is the mean effective pressure which gives an indication of engine displacement utilization for this conversion. Higher the mean effec- tive pressure, higher will be the power developed by the engine for a given displacement.

Again we see that the horsepower of an engine is dependent on its size and speed. Therefore, it is not possible to compare engines on the basis of either horsepower or torque. Mean effective pressure is the true indication of the relative performance of different engines.

3. **Specific output**. Specific output of an engine is defined as the brake output per unit of piston displacement and is given by

$$\text{Specific output} = \text{b.p.}/A \times L$$
$$= \text{constant} \times \text{bmep} \times \text{rpm} \tag{18.12}$$

Thus the specific output consists of two elements – the force available to work and the speed with which it is working. Thus for the same piston displacement and bmep an engine running at higher speed will give more output.

It is clear that the output of an engine can be increased by increasing either speed or bmep. Increasing speed involves increase in the mechanical stresses of various engine parts whereas increasing bmep requires better heat release and more load on engine cylinder.

4. **Volumetric efficiency**. Volumetric efficiency of an engine is an indication of the measure of the degree to which the engine fills its swept volume. It is defined as the ratio of the mass of air inducted into the engine cylinder during the suction stroke to the mass of the air corresponding to the swept volume of the engine at atmospheric pressure and temperature. *Alternatively*, it can be defined as the ratio of the actual volume inhaled during suction stroke measured at intake conditions to the swept volume of the piston.

Volumetric efficiency, η_v

$$= \frac{\text{Mass of charge actually induced}}{\text{Mass of charge corresponding to the cylinder volume at intake pressure and temperature}} \quad (18.13)$$

The volumetric efficiency of an engine puts a limit on the amount of fuel which can be efficiently burned in an engine because the power output is proportional to the amount of air inducted.

For supercharged engines the volumetric efficiency has no meaning as it comes out to be more than unity.

5. **Fuel-air ratio (F/A).** Fuel-air ratio (F/A) is the ratio of the mass of fuel to the mass of air in the fuel-air mixture. Air-fuel ratio (A/F) is reciprocal of fuel-air ratio. Fuel-air ratio of the mixture affects the combustion phenomenon in that it determines the flame propagation velocity, the heat release in the combustion chamber, the maximum temperature and the completeness of combustion.

Relative fuel-air ratio is defined as the ratio of the actual fuel-air ratio to that of the stoichiometric fuel-air ratio required to burn the fuel supplied.

$$\text{Relative fuel-air, ration, } F_R = \frac{\text{Actual fuel-air ratio}}{\text{Stoichiometric fuel-air ratio}} \quad (18.14)$$

6. **Specific fuel consumption.** Specific fuel consumption is defined as the amount of fuel consumed per unit of power developed per hour. It is a clear indication of the efficiency with which the engine develops power from fuel.

$$\text{Specific fuel consumption (sfc)} = \frac{\text{Fuel consumed in gms/hr}}{\text{Horse power developed}} \quad (18.15)$$

Brake specific fuel consumption (bsfc) is determined on the basis of brake output of the engine while indicated specific fuel consumption (isfc) is determined on the basis of indicated output of the engine.

This parameter is widely used to compare the performance of different engines.

7. **Thermal efficiency and heat balance.** Thermal efficiency of an engine is defined as the ratio of the output to that of the chemical energy input in the form of fuel supply. It may be based on brake or indicated output. It is the true indication of the efficiency with which the thermodynamic input is converted into mechanical work. Thermal efficiency, in this definition, accounts for combustion efficiency, *i.e.*, for the fact that whole of the chemical energy of the fuel is not converted into heat energy during combustion.

Brake thermal efficiency = (b.p.)/(m_f × C.V.) (18.16)

where 632.5 kcal is one horsepower-hour equivalent

C.V. = calorific value of fuel, kJ/kg

m_f = mass of fuel supplied,

The energy input to the engine goes out in various forms – a part is in the form of brake output, a part goes into exhaust, and the ret is taken by cooling water and the lubricating oil. The break-up of the total energy input into these different parts is called the *heat balance*. The main components in a heat balance are brake output, coolant losses, heat going to exhaust, radiation and other losses. Preparation of heat balance sheet gives us an idea about the amount of energy wasted in various parts and allows us to think of methods to reduce the losses so incurred.

8. **Exhaust smoke and other emissions**. Smoke and other exhaust emissions such as oxides of nitrogen, unburned hydrocarbons, etc., are nuisance for the public environment. With increasing emphasis on air pollution control all efforts are being made to keep them minimum.

Smoke is an indication of incomplete combustion. It limits the output of an engine if air pollution control is the consideration.

Exhaust emissions have of late become a matter of grave concern and with the enforcement of legislation on air pollution in many countries, it has become necessary to view them as performance parameters.

9. **Specific weight**. Specific weight is defined as the weight of the engine in kg for each brake power developed and is an indication of the engine bulk. Specific weight plays an important role in applications such as power plants for aircrafts.

18.3 BASIC MEASUREMENTS

The basic measurements which usually should be undertaken to evaluate the performance of an engine on almost all tests are the following:

1. Speed.
2. Fuel consumption.
3. Air consumption.
4. Smoke density.
5. Brake power.
6. Indicated power and friction power.
7. Heat going to cooling water.
8. Heat going to exhaust.
9. Exhaust gas analysis.

In addition to above a large number of other measurements may be necessary depending upon the aim of the test.

18.9 MEASUREMENT OF BRAKE POWER

Measurement of brake horsepower is one of the most important measurements in the test schedule of an engine. It involves the determination of the torque and the angular speed of the engine output shaft. This torque measuring device is called a dynamometers.

Dynamomters can be broadly classified into two main types, absorption dynamometers and transmission dynamometer.

Fig. 18.14 shows the basic principle of a dynamometer. A rotor driven by the engine under test, is electrically, hydraulically or magnetically

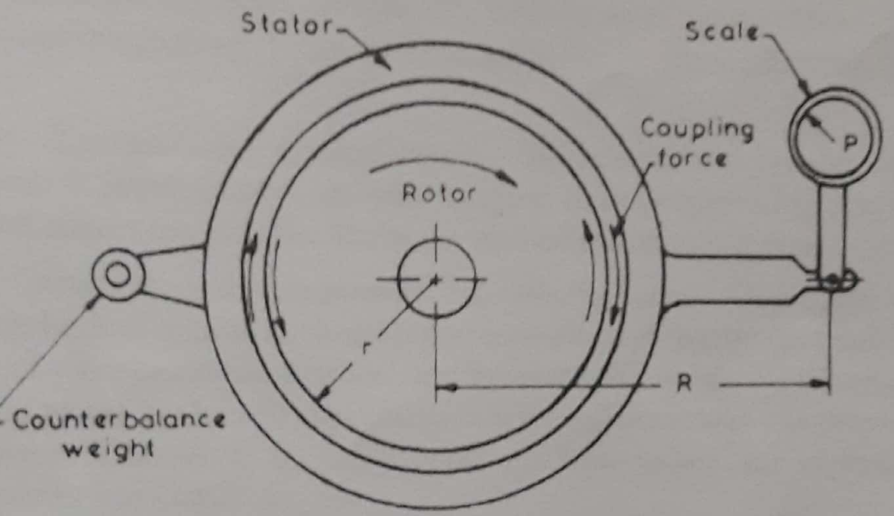

Fig. 18.14 The dynamometer principle

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

$$W = 2\pi r F \qquad (18.22)$$

The external moment or torque is equal to $P \times R$ where P is the scale reading and R is the arm. This moment balances the turning moment $r \times F$, i.e.

$$P \times R = r \times F$$

$\therefore$ Work done/revolution $= 2\pi P R$

Work done/sec $= 2\pi P R N$

where N is rev/s. Hence power is given by

$$\text{Power} = 2\pi RN \tag{18.23}$$

(a) **Absorption dynamometers**. These dynamometers measure and absorb the power output of the engine to which they are coupled. The power absorbed is usually dissipated as heat by some means. Examples of such dynamometers are prony brake, rope brake, hydraulic dynamometer, etc.

(b) **Transmission dynamometers**. In transmission dynamometers the power is transmitted to the load coupled to the engine after it is indicated on some type of scale. These are also called torque-meters.

18.9.1. Absorption dynamometers. 1. *Prony brake*. One of the simplest methods of measuring horsepower is to attempt to stop the engine by means of a 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 works on the principle of converting power into heat by dry friction. It consists of a wooden block mounted on a flexible rope or band (see Fig.. 18.15). The wooden block when pressed into contact with the rotating drum takes the engine torque and the power is dissipated in frictional resistance. Spring-loaded bolts are provided to tighten the wooden block and hence increase the friction. The whole of the power

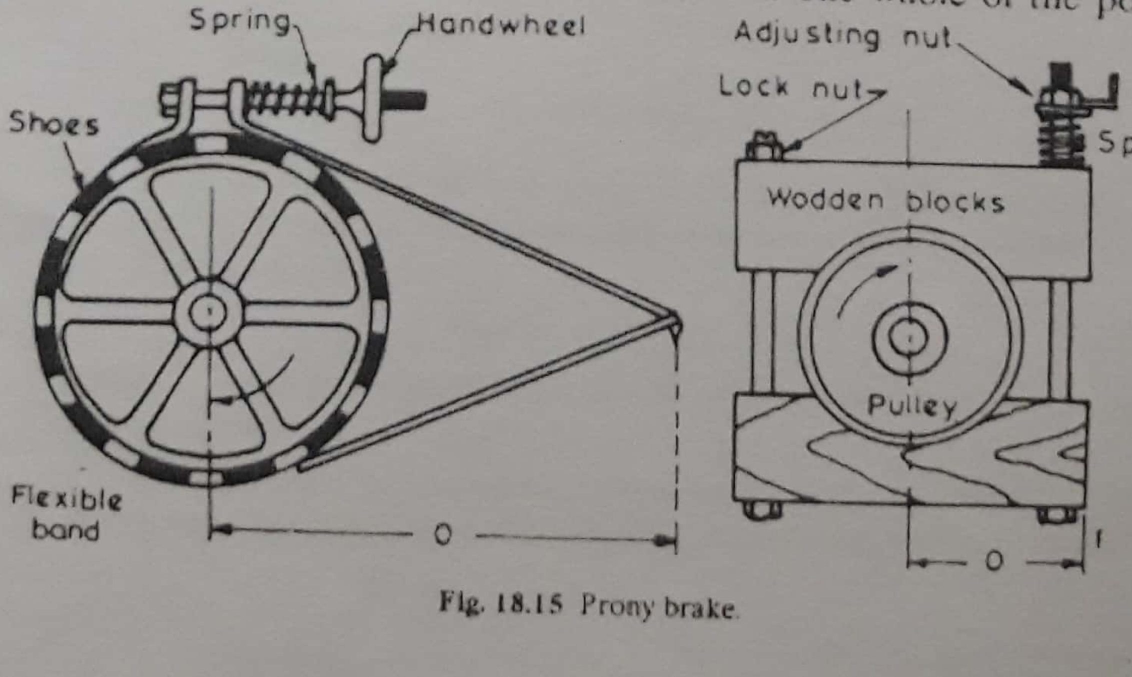

Fig. 18.15 Prony brake.

absorbed is converted into heat and hence this type of dynamometer must be cooled. The brake horsepower is given by

$$\text{b.p.} = 2\pi NT$$

where

$$T = W \times r \qquad (18.24)$$

W being the weight applied at a radius r.

2. *Rope brake.* The rope brake as shown in Fig. 18.16 is another simple device for measuring b.p. 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 is absorbed in friction between the rope and the drum. The drum therefore requires cooling.

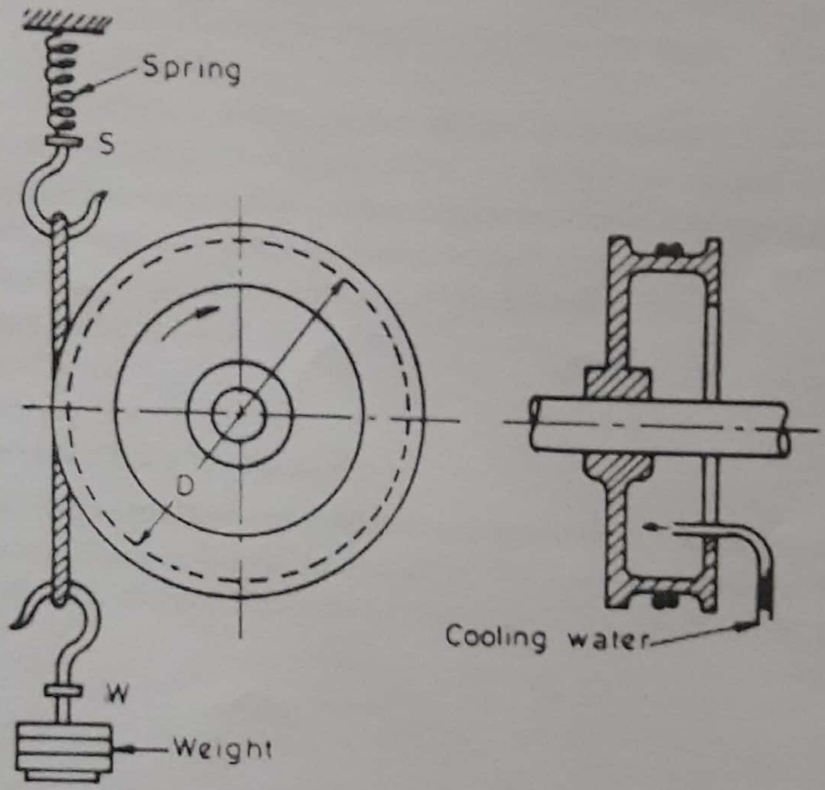

Fig. 18.16 Rope brake.

Rope brake is cheap and easily constructed but not very accurate because of changes in the friction coefficient of the rope with temperature.

The b.p. is given by

$$\text{b.p.} = \pi DN(W - S) \qquad (18.25)$$

where D is the brake drum diameter, W is the weight and S is the spring scale reading.

3. *Hydraulic dynamometer.* Hydraulic dynamometer (Fig. 18.17) works on the principle of dissipating the power in fluid friction rather than

18.10 MEASUREMENT OF FRICTION POWER

The link between the brake power output and indicated power output of an engine is its friction power. Friction has a dominating effect on the performance of an engine. Almost invariably, the difference between a good engine and a bad engine is due to difference between their frictional losses. The frictional losses are ultimately dissipated to the cooling system (and exhaust) as they appear in the form of frictional heat and this influences the cooling capacity required. Moreover lower friction means availability of more brake power, hence brake specific fuel consump- tion is lower. This fuel economy is important because it decides the speed at which an engine can be run economically. The bsfc rises with an increase in speed and at some speed it renders the use of engine prohibitive. Thus the level of friction decides the maximum output of the engine which can be obtained economically.

For reasons outlined above, in the design and testing of an engine measurement of friction power is important for getting an insight into the methods by which the output of an engine can be increased. In the evaluation of i.p. and mechanical efficiency measured friction power is also used. The friction power of an engine is determined by the following method:

1. Willan's line method.
2. Morse test.
3. Motoring test.
4. Difference between i.p. and b.p.

1. **Willan's line method channel rate extrapolation.** In this method gross fuel consumption *vs*. b.p. at a constant speed is plotted and the graph is extrapolated back to zero fuel consumption (see Fig. 18.22). The point

where this graph cuts the b.p. 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 blowby.

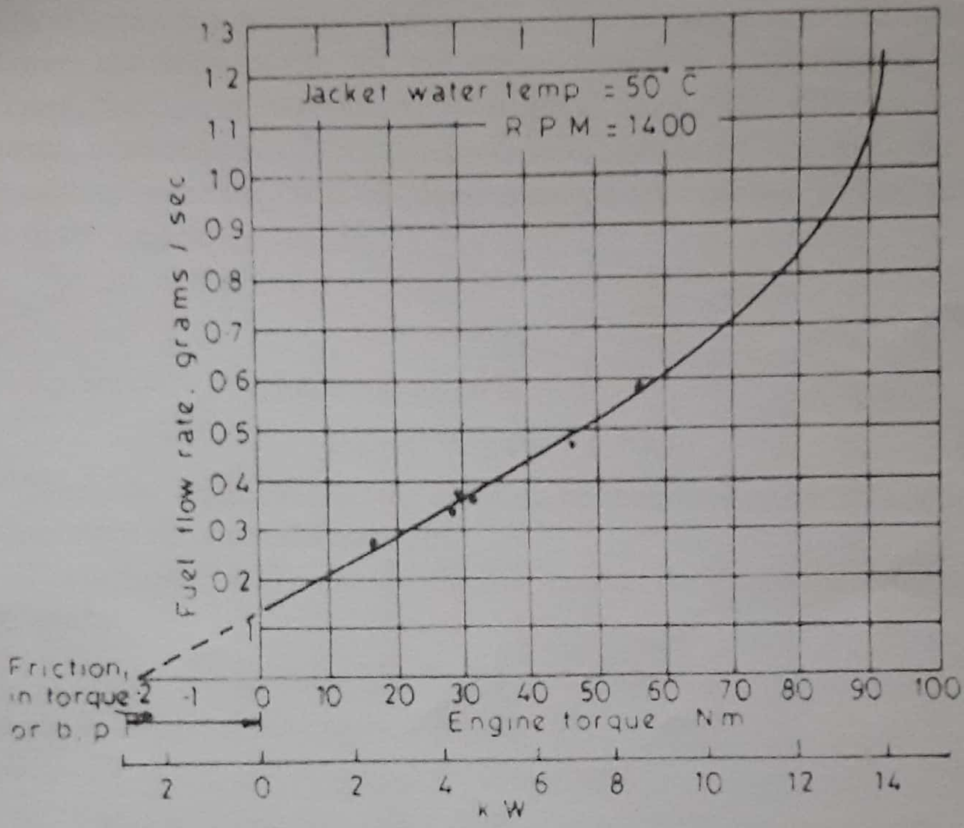

Fig. 18.22 Willan's line method.

The test is applicable only to compression ignition engines.

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. The directional margin of error is rather wide because the graph is not a straight line. The changing slope along the curve indicates part efficiencies of increments of fuel. The pronounced change in the slope of this line near fuel load reflects the limiting influence of the air-fuel ratio and of the quality of combustion. 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. Therefore, it is essential that great care should be taken in extrapolating the line and as many readings as possible should be taken at light loads to establish the true nature of the curve.

The Willan's line for a swirl-chamber CI engine is more straight than that for a direct injection type engine.

The accuracy obtained in this method is good and compares favourably with other methods if extrapolation is carefully done.

2. Morse test In the Morse test, which is applicable only to multi-cylinder engines, the engine is first run at the required speed and the output is mesured. Then one cylinder is cut out by short circulating the spark plug or by disconnecting the injector as the case may be. Under this condition all other cylinders 'motor' this cut-out cylinder. The output is measured by keeping the speed constant at its original value. The difference in the outputs is a measure of the indicated power of the cut-out cylinder. Thus for each cylinder the i.p. is obtained and is added together to find the total i.p. of the engine.

The i.p. of n cylinders is given by

$$\text{i.p.}_n = \text{b.p.}_n + \text{f.p.} \tag{18.26}$$

i.p. for $(n-1)$ cylinders is given by

$$\text{i.p.}_{n-1} = \text{b.p.}_{n-1} + \text{f.p.} \tag{18.27}$$

Since the engine is running at the same speed it is quite reasonable to assume that f.p. remains constant.

From Eqs. (18.17) and (18.18), we see that the i.p. of the nth cylinder is given by

$$(\text{i.p.})\,n\text{th} = \text{b.p.}_n = \text{b.p.}_{n-1} \tag{18.28}$$

and the total i.p. of the engine is

$$\text{i.p.}_n = \Sigma\,(\text{i.p.})\,n\text{th} \tag{18.29}$$

By subtracting bp_n from this the f.p. of the engine can be obtained.

This method though gives reasonably accurate results is liable to errors due to changes in mixture distribution and other conditions by cutting-out one cylinder. In gasoline engines, where there is a common manifold for two or more cylinders the mixture distribution as well as the volumetric efficiency both change. Again, almost all engines have a common exhaust manifold for all cylinders and cutting-out of one cylinder may greatly affect the pulsations in exhaust system which may significantly change the engine performance by imposing different back pressures.

4. Difference between i.p. and b.p. The method of finding the f.p. by computing the difference between i.p., as obtained from an indicator diagram, and b.p., as obtained by a dynamometer is the ideal method. However, due to difficulties in obtaining accurate indicator diagrams, especially at high engine speed, this method is usually mainly used in research laboratories.

Comparison of methods of measuring f.p. The Willan's line method and Morse tests are very cheap and 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 much more powerful tool. As far as accuracy is concerned the i.p.-b.p. method is most accurate if carefully done. Motoring method usually gives a higher value for f.p. as compared to that given by the Willan's line method.

18.11 MEASUREMENT OF INDICATED POWER

There are two methods of finding the i.p. of an engine:

(i) by taking an indicator diagram with the help of a suitable engine indicator, or

(ii) by measuring b.p. and f.p. separately and adding the two.

18.11.1. Indicator diagram. The device which measures the variation of the pressure in the cylinder over a part or full cycle is called an *indicator* and the plot of such information obtained is called an *indicator diagram*. Indicator diagram is the only intermediate record available in the account of total energy liberated before it is measured at the output shaft. Thus an indicator diagram gives a very good indication of the process of converting heat into mechanical work. A great insight can be obtained into combustion phenomenon and in the associated factors such as rate of pressure rise, ignition lag, etc., by its analysis. Also the losses occurring in the induction and exhaust strokes can be studied. It is very rate that an indicator diagram is taken to find i.p. only. It is almost invariably used to study engine combustion, detonation, tuning of inlet and exhaust manifolds, etc.

Basically there are two types of indicator diagrams which can be taken from various indicators. These are:

(i) Pressure-volume (p-v) plot

(ii) Pressure-crank angle (p-θ) plot.

Both types of indicator diagrams are mutually convertible and as discussed later, some indicators can take only p-v diagram while others can take only p-θ diagram. The p-θ diagram is more important and revealing of the two.

18.11.2. Engine indicators. Basically an engine indicating device consists of:

(i) a pressure sensing device,

(ii) a device for sensing the piston displacement or the angular position of the piston over the complete cycle, and

(iii) a display device which can depict both pressure and piston displacement on one set of paper or screen.

Some indicators also need additional circuitry such as pre-amplifier to amplify the pressure signal before it can be displayed.

The main types of engine indicators are:

1. Piston indicator.
2. Balanced diaphragm type indicator.

Problems for the Performance Analysis of IC Engines

1. The air flow to a four cylinder four stroke petrol engine is measured by means of a 7.5 cm diameter sharp-edged orifice, C_d=0.6. During a test on the engine following data were recorded.
   Bore=11 cm, stroke=13 cm, engine speed=2250 rev/min, brake power=36 kW, fuel consumption=10.5 kg/h, calorific value of fuel=42000 kJ/kg, pressure drop across the orifice=4.1 cm of water. Atmospheric temperature and pressure are 30^0C and 1.01325 bar.
   Calculate:
   (a) Brake thermal efficiency, (b) brake mean effective pressure and (c) volumetric efficiency based on the free air conditions.

2. A gas engine working on the constant volume cycle gave the following results during a one hour test run. Cylinder diameter=24 cm, stroke=48 cm, effective diameter of brake wheel=1.25 m, net load on brake=1236 N, average speed=227 rpm, average explanation per minute=77, mean effective pressure of indicator cards=7.5 bar, gas used, 13 m^3 at 25^0C and 770 mm of mercury, lower calorific value of gas=22000 kJ/m^3 at N.T.P. Cooling water used=625 kg, inlet temperature=30^0C and outlet temperature=60^0C.
   Determine:
   (a) the mechanical Efficiency, (b) the gas consumption in m^3 at N.T.P. per i.p. hour and (c) the indicated thermal efficiency.
   Prepare a heat balance sheet for the engine on minute basis. Explain why the friction power has been included in or omitted from the heat balance. N.T.P. conditions are 760 mm of mercury and 0^0C.

3. A two-stroke CI engine develops a brake power of 368 kW while its friction power is 74 kW. Its fuel consumption is 180 kg/h and works with an air-fuel ratio of 18:1. The heating value of the fuel is 42000 kJ/kg. Determine (a) indicated power, (b) mechanical efficiency, (c) air consumption per hour, (d) indicated thermal efficiency and (e) brake thermal efficiency.

4. A four-stroke SI engine delivers a brake power of 440 kW with a mechanical efficiency of 88%. The measured fuel consumption is 160 kg of fuel in one hour and air consumption is 410 kg during one fifth of an hour. The heating value of the fuel is 42000 kJ/kg. Estimate (a) indicated power, (b) friction power, (c) air-fuel ratio, (d) indicated thermal efficiency and (e) brake thermal efficiency.

5. The following details were noted in a test on a four cylinder, four-stroke engine, diameter=100 mm, stroke=120 mm, speed of the engine=1600 rpm, fuel consumption=0.2 kg/min, calorific value of fuel=44000 kJ/kg, difference in tension on either side of the brake pulley=40 kg, brake circumference is 300 cm. If the mechanical efficiency is 80%, calculate (a) brake thermal efficiency, (b) indicated thermal efficiency, (c) indicated mean effective pressure and (d) brake specific fuel consumption.

6. A four-stroke cycle gas engine has a bore of 20 cm and a stroke of 40 cm. The compression ratio is 8. In a test on the engine, the indicated mean effective pressure is 6 bar, the air to gas ratio is 6:1 and the calorific value of the gas is 12 MJ m^3 at N.T.P. At the beginning of the compression stroke, the temperature is 78^0C and pressure 1.0 bar. Neglecting residual gases, determine the indicated power, the thermal efficiency and the relative efficiency of the engine at 250 rpm.

7. A four-stroke four-cylinder gasoline engine has a bore of 60 mm and a stroke of 100 mm. On test it develops a torque of 66.5 Nm when running at 3000 rpm. If the clearance volume in each cylinder is 60 cc, the relative efficiency with respect to brake thermal efficiency is 0.5 and the calorific value of the fuel is 42 MJ/kg, determine the fuel consumption in kg/h and the brake mean effective pressure.

8. A gas engine having a cylinder 250 mm bore and 450 mm stroke has a volumetric efficiency of 80%. Air-gas ratio is 10:1 and calorific value of fuel 21000 kJ/m^3 at NTP. Calculate the heat supplied to the engine per working cycle. If the compression ratio is 6:1, what is the heat value of the mixture per working stroke per m^3 of total cylinder volume?

9. A certain engine at full load delivers a brake power of 36.8 kW. It requires a friction power of 7.36 kW to rotate the engine without fuel at the same speed. Calculate its mechanical efficiency. Assuming that the mechanical losses remain constant what will be the mechanical efficiency at (a) half load and (b) quarter load?

18.1. Petrol engine : $\eta_{overall}$ bmep;; η_{vol}

The air flow to a four cylinder four stroke petrol engine is measured by means of a 7.5 cm diameter sharp-edged orifice, C_d = 0.6. During a test on the engine following data were recorded.

Bore = 11 cm, stroke = 13 cm, engine speed = 2250 rev/min, brake power = 36 kW, fuel consumption = 10.5 kg/h, calorific value of fuel = 42,000 kJ/kg., pressure drop across the orifice = 4.1 cm of water. Atmospheric temperature and pressure are 15°C and 1.013 bar.

Calculate:

(a) *Thermal efficiency on b.p. basis*

(b) *Brake mean effective pressure.*

(c) *Volumetric efficiency based on free airconditions.*

Solution.

(a) Brake thermal efficiency

$$= \frac{\text{kW} \times 3600}{\dot{m}_f/\text{hr} \times \text{C.V.}}$$

$$= \frac{36 \times 3600}{10.5 \times 42000} = 0.294 \qquad \textbf{Ans.}$$

(b) Brake mean effective pressure

$$= \frac{\text{b.p./cylinder}}{LAN}$$

$$= \frac{36}{4} \times \frac{1}{(\pi/4)\,(0.11)^2 \times 0.13} \times \frac{1}{(2250/60)}$$

$$= 3.885 \text{ bar} \qquad \textbf{Ans.}$$

(c) Volumetric efficiency $= \dfrac{\text{vol. of air inhaled}}{\text{swept volume}}$

$$\text{Air inhaled/s} = C_d A_{\text{orifice}} \sqrt{2\,\Delta p \cdot \rho_{air}}$$

$$\Delta p = 4.1 \text{ cm } H_2O = \rho g h \text{ N/m}^2$$

$$= 1000 \times 9.807 \times \frac{4.1}{100} = 402.09 \text{ N/m}^2$$

$$\rho_{\text{air}} = \frac{p}{RT} = \frac{1.013 \times 10^2}{0.287 \times 288} = 1.226 \text{ kg/m}^3$$

$$\therefore \quad \text{Air inhaled/s} = 0.6 \times \frac{\pi}{4}\left(\frac{7.5}{100}\right)^2 \sqrt{2 \times 402.09 \times 1.226}$$

$$= 0.0832 \text{ kg/s}$$

$$\text{Swept volume/s} = \text{No. of cylinders} \times \frac{\pi}{4} d^2 l \times (\text{workingcycles/s})$$

$$= 4 \times \frac{\pi}{4} \times (0.11)^2 \times 0.13 \times \frac{2250}{2 \times 60}$$

$$= 0.0927 \text{ m}^3/\text{s}$$

$$\text{Volumetric efficiency} = \frac{0.0832}{0.0927} = 0.898 \qquad \textbf{Ans.}$$

18.2. Gas engine: η_{mech}: gas consumption; $\gamma_{indicated}$

A gas engine working on the constant volume cycle gave the following results during a one-hour test run. Cylinder diameter 24 cm; stroke, 48 cm; effective diameter of brake wheel, 1.25 m. Net lead on brake 1236 N; average speed 226.7 rev/min; average explanation per minute, 77; mep of indicator cards, 7.5 bar; gas used, 13 m^2 at 15°C and 771 mm of mercury pressure; lower calorific value of gas, 22000 kJ/m^3 at N.T.P. Cooling water used, 625 kg; inlet temperature, 25°C. Outlet temperature, 60°C.

Determine:

(a) *The mechanical efficiency.*

(b) *The gas consumption in m^3 at N.T.P. per i.p. hour.*

(c) *The indicated thermal efficiency.*

Draw up a heat balance for the engine on minute basis. Explaining why the friction power has been included in or omitted from the heat balance. N.T.P. conditions are 760 mm of mercury and 0°C.

Solution.

(a) $$\text{b.p.} = 2\pi NT$$

$$= 2\pi \times \left(\frac{226.7}{60}\right) \times (1236 \times 1.25) \times \frac{1}{10^3} \text{ kW}$$

$$= 18.34 \text{ kW}$$

$$\text{i.p.} = p_m LAN$$

$$= (7.5 \times 10^2) \times 0.48 \times \frac{\pi}{4}(0.24)^2 \times \left(\frac{77}{60}\right) \text{ kW}$$

$$= 20.9 \text{ kW}$$

$$\therefore \quad \text{Mechanical efficiency} = \frac{\text{b.p.}}{\text{i.p.}}$$

$$= \frac{18.34}{20.9} = 0.878 \text{ or } 87.8\% \qquad \textbf{Ans.}$$

(b) Gas consumption at N.T.P., i.e. 0°C and 760 mm Hg

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

or $$\frac{771 \times 13}{288} = \frac{760 \times v_2}{273}$$

$\therefore$ $$v_2 = \frac{771}{760} \times 13 \times \frac{273}{288} = 12.5 \text{ m}^3/\text{hr}$$ **Ans.**

(c) Indicated thermal efficiency $= \dfrac{\text{i.p.} \times 3600}{V_{\text{fuel}} \times \text{C.V.}}$

$$= \frac{20.9 \times 3600}{13 \times 22000} = 0.263 \text{ or } 26.3\%$$ **Ans.**

(d) Heat balance sheet on minute basis:

Heat supplied/min $= \dfrac{12.5}{60} \times 22{,}000 = 4583.3$ kJ/min

Heat equivalent to b.p. $= 18.34 \times 60 = 1100.4$ kJ/min

Heat in cooling water $= m_w \times C_p \times \Delta T$

$$= \frac{625}{60} \times 4.1868 \times (60 - 25) = 1526.4 \text{ kJ/min}$$

	Heat supplied by gas	= 4583.3 kJ/min, 100%
1.	Heat equivalent to b.p.	= 1100.4 kJ/min, 24.0%
2.	Heat in cooling water	= 1526.4 kJ/min, 33.3%
3.	Heat to exhaust, radiation, etc.	= 1956.5 kJ/min, 42.7%
	Total	4583.3 kJ/min, 100% **Ans.**

Friction is not included in heat balance sheet, as finally friction is rejected to cooling water, exhaust, radiation, etc.

18.3. Oil engine; heat balance

A test on a single cylinder, four stroke oil engine having bore 18 cm and stroke 36 cm yielded the following results; speed 285 rev/min; brake torque, 393 Nm; indicated m.e.p., 7.2 bar; fuel consumption, 3.5 kg/hr; cooling water flow, 4.5 kg/min; cooling water temperature rise 36°C; air-fuel ratio by mass, 25; exhaust gas temperature, 415°C; barometric pressure, 1.013 bar; room temperature 21°C.

The fuel has a calorific value of 45200 kJ/kg and contains 15% by mass of hydrogen. Determine

(a) *the indicated thermal efficiency,*

(b) *the volumetric efficiency based on atmospheric conditions.*