Chapter 1

Internal Combustion Engines

1.1 Performance Parameters

Engine performance parameters can be measured by two means; the *indicator* equipment or the *dynamometer*.

The indicator system consists of a *pressure indicator* (pressure transducer), *crank angle encoder* and a *tachometer*. The purpose is to obtain the pressure inside the cylinder. This pressure reading along with the crank angle reading enables us to construct the p-v diagram (indicator diagram) of the gas inside the cylinder for the complete cycle. From the p-v diagram, we may obtain the work done by the gas by measuring the area of the p-v diagram. Combining with the engine speed reading from the tachometer, we may find the power of the engine. All parameters obtained based on the indicator diagram are given the prefix '*indicated*'.

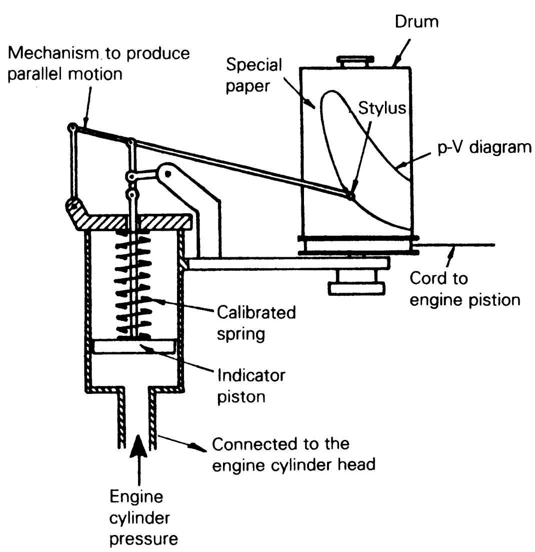

Figure 1.1. Mechanical Indicator

A dynamometer is coupled to the engine crankshaft. It measures the torque produced by the engine. This is done by braking the crankshaft and balancing the resultant torque with a load on an arm. Along with the engine speed obtained from the tachometer, we may calculate the power of the engine. All parameters obtained based on dynamometer reading are given the prefix '*brake*'.

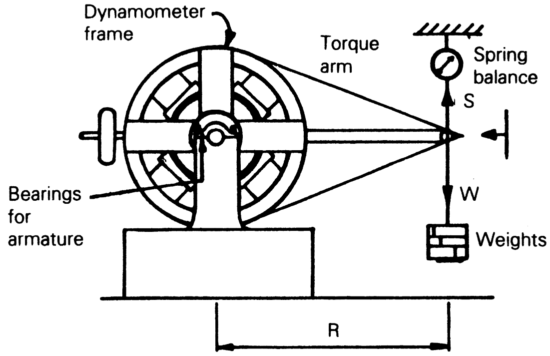

Figure 1.2. Dynamometer

The difference between power produced by the gas inside the cylinder and the power available on the crankshaft is the power lost by friction in the engine components.

1.1.1 Rates

To convert between a quantity and its rate, we have to multiply it with N', known as the number of power strokes per second. For a given engine speed N rpm;

$$N' = \frac{N}{2 \times 60} \qquad \text{(for 4 stroke engines)}$$
$$N' = \frac{N}{60} \qquad \text{(for 2 stroke engines)}$$

Thus, for power-work, mass flow rate - mass, volumetric flow rate - volume;

$$\dot{W} = W \times N'$$
$$\dot{m} = m \times N'$$
$$\dot{V} = V \times N'$$
$$\text{etc.}$$

1.1.2 Mean Piston Speed

Mean piston speed is useful to compare between different engines.

$$\bar{V}_p = \frac{2LN}{60}$$

1.1.3 Indicated Mean Effective Pressure

Indicated Mean Effective Pressure (IMEP $= \mathrm{P_i}$)

$$P_i = \frac{\text{net area of diagram}}{\text{length of diagram}} \times \text{constant}$$

the constant depends on the scale of the recorder. If we are using a mechanical indicator, this constant would be the spring constant.

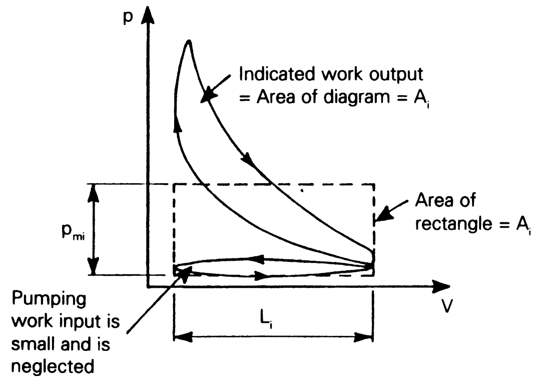

Figure 1.3. Indicator Diagram

1.1.4 Indicated Power

Work done per cycle = Indicated Work = W_i is given by

$$W_i = P_i \times V_d$$

and the displaced volume, V_d is

$$V_d = A \times L \times n$$

where

$A = \text{cylinder cross section} = \dfrac{\pi B^2}{4}$

$B = \text{bore}$

$L = \text{stroke}$

$n = \text{number of cylinders}$

Indicated power = IP is then given by

$$\mathrm{IP} = P_i L\, A\, n\, N'$$

1.1.5 Brake Power

From the dynamometer reading of torque;

$$\tau = WR$$

where W = dynamometer load and R = length of dyno arm, brake power (shaft power) is given as

$$\mathrm{BP} = \frac{2\pi N\tau}{60}$$

1.1.6 Friction Power & Mechanical Efficiency

Friction power is the power lost during transmission from inside the cylinder (indicated power) to the shaft (brake power);

$$\mathrm{FP} = \mathrm{IP} - \mathrm{BP}$$

Thus, we can define the mechanical efficiency of the engine as

$$\eta_m = \frac{\mathrm{BP}}{\mathrm{IP}}$$

Mechanical efficiency is usually between 80 and 90%.

1.1.7 Brake Mean Effective Pressure

From mechanical efficiency, we can write

$$\mathrm{BP} = \eta_m \mathrm{IP}$$

combining with the expression for IP;

$$\mathrm{BP} = \eta_m P_i L\, A\, n\, N'$$

To make the expression of BP look similar to IP, we may write

$$\text{BP} = P_b L A n N'$$

where P_b is defined as the *brake mean effective pressure* (bmep). It is also clear that $P_b = \eta_m P_i$. BMEP can be shown to be independent of engine size.

1.1.8 Thermal Efficiency

Thermal efficiency is basically

$$\eta = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}}$$

If the net power used is the indicated power, we will obtain the *indicated thermal efficiency*;

$$\eta_{\text{IT}} = \frac{\text{IP}}{\dot{m}_f \times \text{fuel calorific value} \, [\frac{\text{kJ}}{\text{kg}}]} = \frac{\text{IP}}{\dot{V}_f \times \text{fuel calorific value} \, [\frac{\text{kJ}}{m^3}]}$$

with $\dot{m}_f$ and $\dot{V}_f$ being the fuel consumption rate in terms of mass or volume respectively.
Similarly, if the brake power is used, we will get the *brake thermal efficiency*;

$$\eta_{\text{BT}} = \frac{\text{BP}}{\dot{m}_f \times \text{fuel calorific value} \, [\frac{\text{kJ}}{\text{kg}}]} = \frac{\text{BP}}{\dot{V}_f \times \text{fuel calorific value} \, [\frac{\text{kJ}}{m^3}]}$$

Noticing the difference of only BP and IP, we may also write the mechanical efficiency as

$$\eta_m = \frac{\eta_{\text{BT}}}{\eta_{\text{IT}}}$$

1.1.9 Specific Fuel Consumption

Specific Fuel Consumption (*sfc*) is the mass flow rate of fuel per unit power output, and is a measure of engine economy;

$$\text{sfc} = \frac{\dot{m}_f}{\text{BP}}$$

sfc can be used to compare the economy of engines of different sizes.

Recognizing the ratio $\frac{\dot{m}_f}{\text{BP}}$ in brake thermal efficiency, we may also write brake thermal efficiency as

$$\eta_{\text{BT}} = \frac{1}{(\text{sfc}) \times \text{calorific value} \, [\frac{\text{kJ}}{\text{kg}}]}$$

1.1.10 Volumetric Efficiency

This is also called the breathing capacity of the engine to see how well it can induce air into the cylinder. For naturally aspirated engines, this is usually below 80%, meaning that the air getting into the cylinder is only 80% of what should be filling the cylinder. This may be due to differing temperatures and pressures between inside and outside the engine. The compressible nature of air also means that it needs enough time to flow into and fill the cylinder properly. Compression ratio and clearance volume also play a big role affecting volumetric efficiency apart from other factors.

$$\eta_v = \frac{m_a}{m_d} = \frac{\text{mass of air getting into the cylinder}}{\text{mass of air that should fill the displaced volume at free air condition}}$$

The free air condition is taken as the atmospheric condition, P_0 and T_0. Thus, to fill the displaced volume, V_d, at this condition, the mass is $m_d = \frac{P_0 V_d}{R T_0}$.

We may also define it in terms of volumes;

$$\eta_v = \frac{V_a}{V_d} = \frac{\text{volume of air getting into the cylinder w.r.t free air condition}}{\text{displaced volume of cylinder}}$$

with $V_a = \frac{m_a R T_0}{P_0}$

In terms of rates;

$$\eta_v = \frac{\dot{m}_a}{\dot{m}_d} = \frac{\dot{V}_a}{\dot{V}_d}$$

1.2 Engine Testing

Engine testing is usually done by two methods; *constant speed test* and *variable speed test*. In a constant speed test, the load is varied but the speed is adjusted to the same value in response to changes in load. While in a variable speed test, the fuel supply is set constant while the load is varied. This would cause change in speed. In a petrol engine, the fuel supply is maintained steady by holding the throttle opening constant. While in a diesel engine, this is done by setting the fuel rack constant.

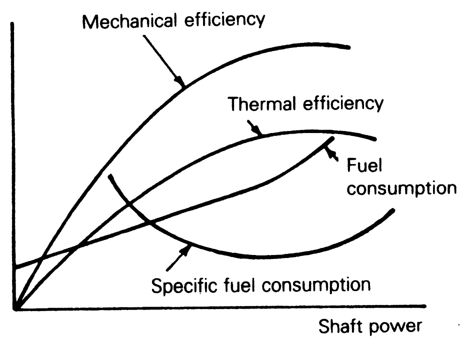

Figure 1.4. Typical Constant Speed Test Results

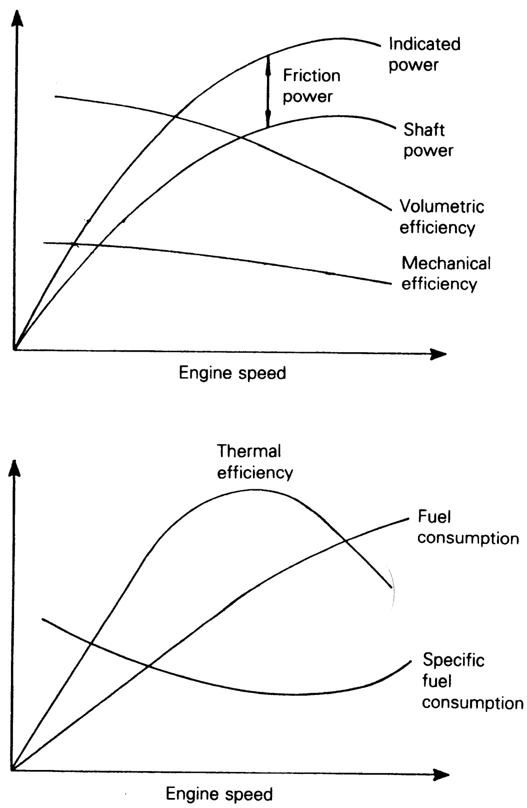

Figure 1.5. Typical Variable Speed Test Results

1.2.1 Morse Test

Morse test is sometimes called the cutoff test. This is done to estimate the indicated power of an engine only using a dynamometer (no indicator needed). This test is applicable only to multicylinder engines. The assumption is that, at the same speed, the friction power is the same whether all cylinders are firing or if one of them is not firing (but still moving due to crankshaft movement).

First, the brake power is measured for the engine with all cylinders firing. Then one cylinder is cut off by disconnecting the spark plug or injector (for SI or CI engines respectively). The speed will fall, but is restored by reducing the load. Brake power is measured again in this condition. Then the firing of that cylinder is restored, and the next cylinder is cut out in turn. The preceding procedure is repeated for all cylinders.

First the torque with all cylinder firing is measured, thus we get $\mathrm{BP} = \frac{2\pi N\tau}{60}$. The IP is thus IP=BP+FP.

With the first cylinder off, the torque is measured to give us $\mathrm{BP}_{1-} = \frac{2\pi N\tau}{60}$. IP when 1 cylinder is off is then $\mathrm{IP}_{1-} = \mathrm{BP}_{1-} + \mathrm{FP}_{1-}$. But since FP is assumed to remain the same in either case,

$$\begin{aligned} \mathrm{IP} &= \mathrm{BP} + \mathrm{FP} && \text{(all cylinders firing)} \\ \mathrm{IP}_{1-} &= \mathrm{BP}_{1-} + \mathrm{FP}_{1-} && \text{(cylinder one off)} \\ \mathrm{IP} - \mathrm{IP}_{1-} &= \mathrm{BP} - \mathrm{BP}_{1-} && (\text{since } \mathrm{FP} = \mathrm{FP}_{1-}) \end{aligned}$$

$\mathrm{IP} - \mathrm{IP}_{1-}$ is theoretically the indicated power of the off cylinder if it had been firing. Thus, the IP of the first cylinder is

$$\mathrm{IP}_1 = \mathrm{BP} - \mathrm{BP}_{1-}$$

which can be calculated based on just 2 measurements of BP's. For other cylinders;

$$\begin{aligned} \mathrm{IP}_2 &= \mathrm{BP} - \mathrm{BP}_{2-} \\ \mathrm{IP}_3 &= \mathrm{BP} - \mathrm{BP}_{3-} \\ &\vdots \end{aligned}$$

Thus, the total IP for the engine is $\mathrm{IP} = \mathrm{IP}_1 + \mathrm{IP}_2 + \mathrm{IP}_3 + \cdots$ and with the BP calculated initially, the FP and η_m will easily be obtained.