7 INTERNAL COMBUSTION ENGINES

Any type of engine, which derives heat energy from the combustion of fuel and converts this energy into mechanical work, is termed as a *heat engine*.

Heat engines may be classified into two main classes :

1. External combustion (E.C) engine, and
2. Internal combustion (I.C) engine.

If the combustion of the fuel takes place outside the working cylinder then the engine is called the *external combustion engine*. If the combustion takes place inside the working cylinder, the engine is called the *internal combustion engine*.

The most common examples of external combustion engines are the steam engines and steam turbines. Internal combustion engines are used in scooters, cars, buses, trucks, locomotives, agricultural and earth moving machinery, power generation and in may industrial applications.

Advantages of I.C. engines over E.C. engines:

i) High efficiency ii) Simplicity
iii) Compactness iv) Light weight
v) Easy starting, and vi) Comparatively lower cost

Classification of I.C. engines

I.C. engines are classified as given below :

1. *According to cycle of combustion:*
   i) Otto cycle engine ii) Diesel cycle engine
   iii) Dual-combustion cycle engine
2. *According to the fuel used :*
   i) Petrol engine ii) Diesel engine
   iii) Gas engine iv) Kerosene engine, etc.
3. *According to the cycle of operation :*
   i) Two stroke cycle engine ii) Four stroke cycle engine
4. *According to the method of ignition :*
   i) Spark ignition (S.I) engine ii) Compression ignition (C.I) engine
5. *According to the number of cylinders:*
   i) Single cylinder engine ii) Multi cylinder engine

6. *According to the arrangement of cylinders:*
   i) Horizontal engine ii) Vertical engine iii) V-engine
   iv) In-line engine v) Radial engine, etc.
7. *According to the speed of the engine:*
   i) Low speed engine ii) Medium speed engine iii) High speed engine
8. *According to the method of cooling the cylinder :*
   i) Air cooled engine ii) Water cooled engine
9. *According to their uses:*
   i) Stationary engine ii) Automobile engine iii) Aero engine
   iv) Locomotive engine v) Marine engine, etc.

I.C. engine parts and their functions

A cross section of an air cooled I.C. engine with principal parts is shown in fig. 7.1. The functions of different parts of the engine are given below.

Cylinder : The heart of the engine is the cylinder and its primary function is to contain the working fluid under pressure and the secondary function is to guide the piston. To avoid wear of the cylinder block, cylinder liners are provided. The cylinder is made of gray cast iron.

Cylinder head : One end of the cylinder is closed by means of a removable cylinder head which usually contains the inlet valve for admitting air-fuel mixture and exhaust valve for discharging product of combustion. The valves are operated by means of cams geared to the engine shaft. The cylinder head is usually made of cast iron or alloy cast iron containing nickel, chromium and molybdenum.

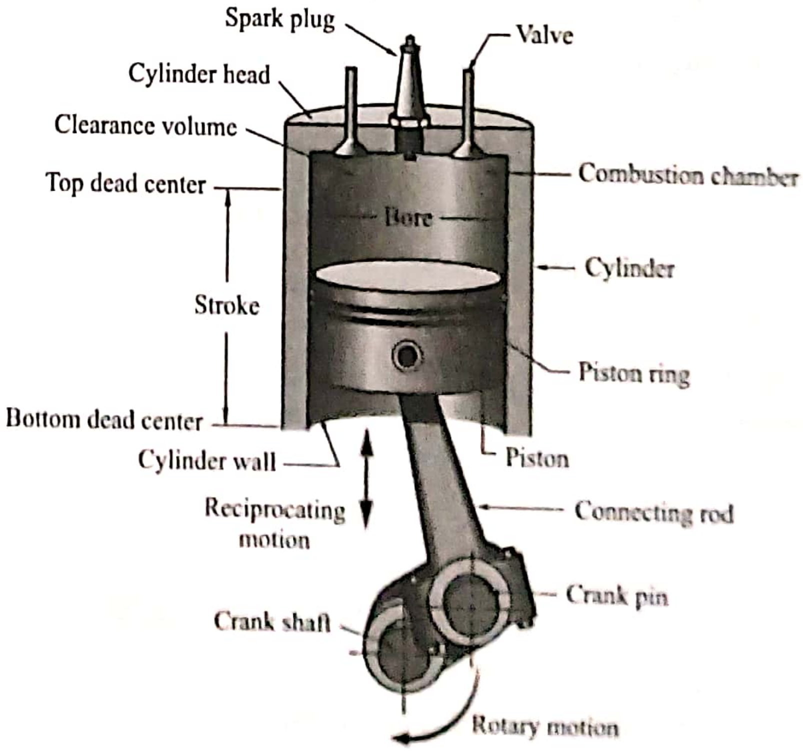

Fig. 7.1 I.C. Engine fundamentals

Piston : (Refer fig. 7.2*a*) The piston used in internal combustion engines is usually of *trunk* type. Such piston is open at one end. The main function of the piston is to receive the impulse from the expanding gas and transmit the energy to the crankshaft through the connecting rod. At the same time, the piston must also disperse a large amount of heat from the combustion chamber to the cylinder walls. Pistons are made of cast iron or aluminum alloys for lightness.

Piston rings : The piston rings may be classified into two groups :

1. Compression ring and 2. Oil control ring.

The compression rings are inserted at the top portion of the piston. Their functions are :

(i) To maintain a pressure tight seal between the piston and the cylinder liner.

(ii) To transfer the heat from the piston head to the cylinder walls.

The function of oil ring is to scrap the lubricating oil from the surface of the liner, so as to minimize the flow of oil into the combustion chamber. Also during the upward motion, these should allow sufficient oil to go upward for the proper lubrication of the liner. Piston rings are made of cast iron.

(a) Piston

(b) Connecting rod

(c) Crank shaft

Fig. 7.2 I.C. engine parts

Connecting rod : (Refer fig. 7.2*b*) One end of the connecting rod known as the small end is connected to the piston through the piston pin and the other end called the big end is connected to the crank through the crank pin. The main function of the connecting rod is to transmit the push and pull from the piston pin to the crank pin. The usual cross-section of the connecting rod is I-section. Connecting rods are made of carbon steel or alloy steel.

Crankshaft : (Refer fig. 7.2*c*) The function of the crankshaft is to transform reciprocating motion into a rotary motion. Crankshafts are made of carbon steel. The shaft portion of the crankshaft revolves in the main bearing. The big end of the connecting rod is connected to the crank pin. The crank web connects the crank pin and the shaft part.

Flywheel : A flywheel is a rotating mass, which is used as an energy storing device. It absorbs mechanical energy by increasing its angular velocity during the power stroke and delivers energy by decreasing its velocity during suction, compression and exhaust strokes. The flywheel is used to smooth out the flow of energy between the engine and its load. The flywheel is made of cast iron. In four stroke engine, the weight of the flywheel used is high.

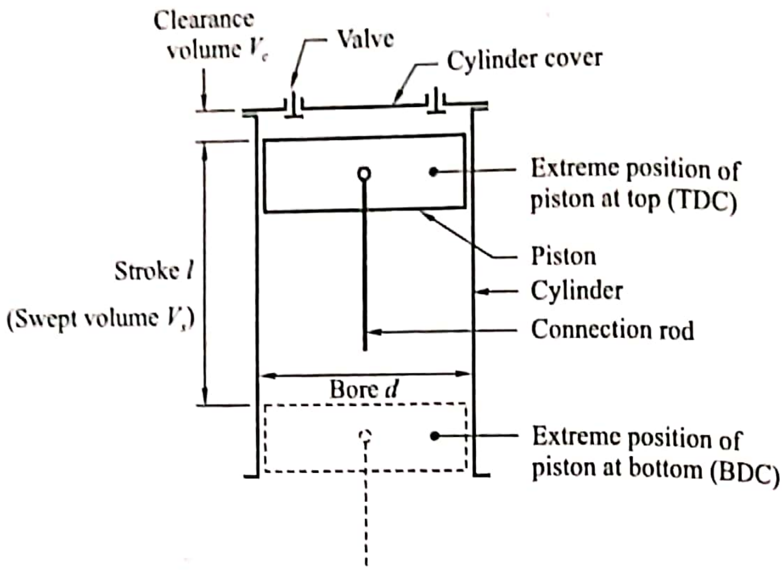

Fig. 7.3 I.C. Engine terminology

I.C. engine terminology (Refer fig. 7.3)

Bore (d) : The inside diameter of the cylinder is called the *bore*.

Stroke (l) : As the piston reciprocates inside the engine cylinder, it has got limiting upper and lower positions beyond which it cannot move and reversal of motion takes place at these limiting positions. The linear distance along the cylinder axis between the two extreme positions of the piston is called *stroke*.

Top dead center (T.D.C) : The top most position of the piston towards cover end of the cylinder is called *top dead center*. In case of horizontal engine, it is called as *inner dead center* (I.D.C).

Bottom dead center (B.D.C) : The lowest position of the piston towards the crank end of the cylinder is called *bottom dead center*. In case of horizontal engine, it is called *outer dead center* (O.D.C).

Clearance volume : The volume contained in the cylinder above the top of the piston, when the piston is at the top dead center is called *clearance volume*.

Compression ratio : It is the ratio of total cylinder volume to the clearance volume.

Let V_c = Clearance volume

V_s = Swept volume = Displacement or stroke volume $= \frac{\pi}{4} d^2 l$

Total cylinder volume $= V_c + V_s$

$$\therefore \text{ Compression ratio } = \frac{V_c + V_s}{V_c}$$

l/d ratio : The size of the engine depends on l/d ratio. If $l = d$, it is called square engine, if $l > d$, it is called under square engine and if $l < d$, it is called over square engine. An over square engine can operate at higher speeds due to larger bore and shorter stroke.

Piston speed: The velocity of the piston v is the linear distance traveled by the piston per unit time.

i.e., $v = 2ln'$ m/s

where l = Length of stroke in m

n' = Speed of the engine in rps

Cycle of operation

The number of strokes of the piston required to complete the cycle varies with the type of the engine. There are two types of engines namely *four-stroke cycle engine* and *two-stroke cycle engine*. A four-stroke engine requires four strokes of the piston or two revolutions of the crankshaft to complete one cycle. In a two-stroke cycle engine there are two strokes of the piston or one revolution of the crankshaft to complete one cycle. The four stroke and two stroke engines are further classified into *petrol engines* and *diesel engines* according to the type of fuel used.

Four-stroke cycle petrol engine

The four-stroke cycle petrol engine operates on *Otto* (constant volume) cycle. Since ignition in these engines is due to a spark, they are also called *spark ignition engines*. The four different strokes are :

(i) Suction stroke, (ii) Compression stroke,

(iii) Working or power or expansion stroke, and (iv) Exhaust stroke.

The construction and working of a four-stroke petrol engine is shown in fig. 7.4. Fig. 7.5. shows a theoretical Otto cycle.

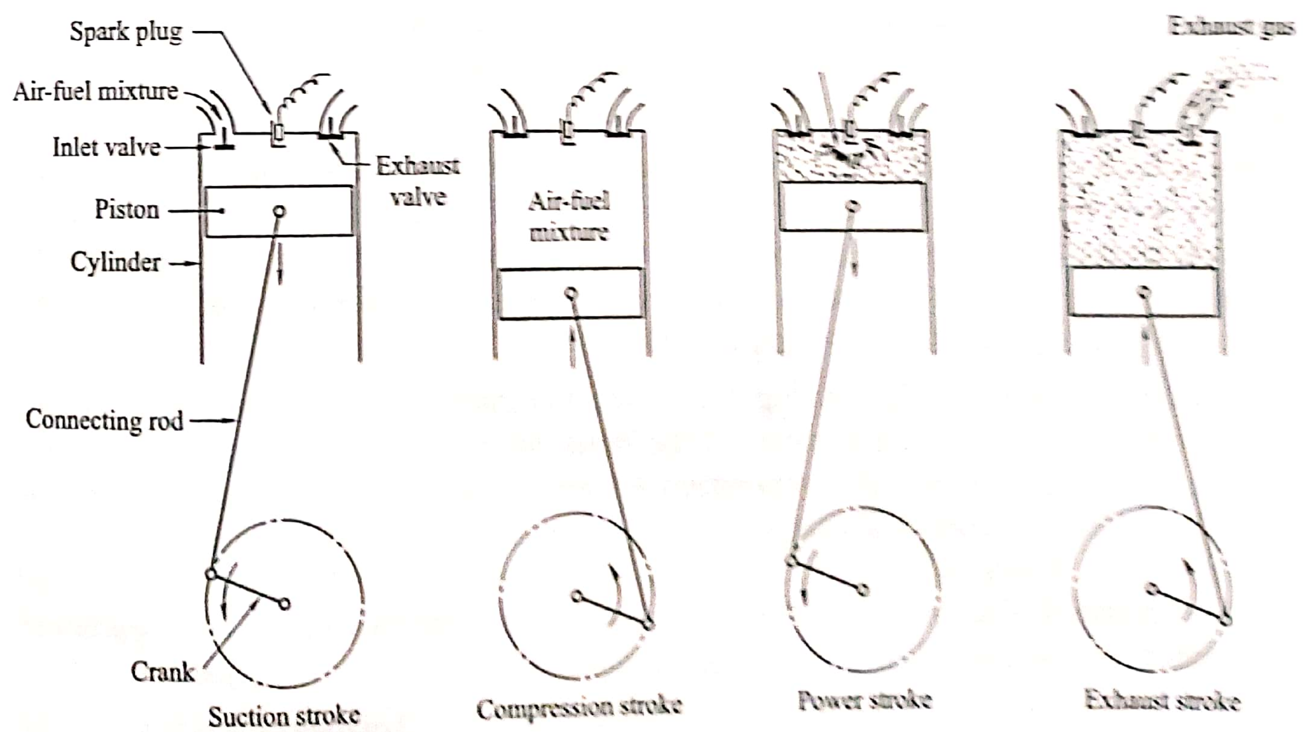

Fig. 7.4 Four stroke cycle petrol engine

Suction stroke (0 to 180°) : During suction stroke, the piston is moved from the top dead center to the bottom dead center by the crankshaft. The crankshaft is revolved either by the momentum of the flywheel or by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The proportionate air-petrol mixture is sucked into the cylinder due to the downward movement of the piston. This operation is represented by the line AB on the P-V diagram (fig. 7.5).

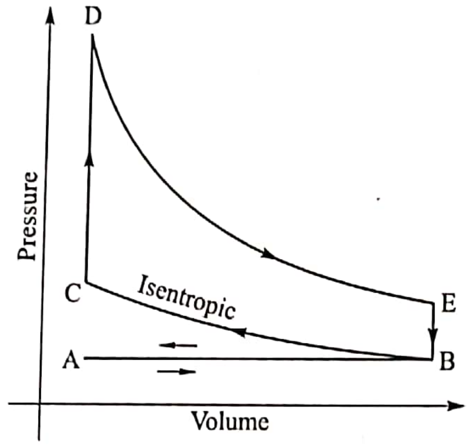

Fig. 7.5 Theoretical Otto cycle

Compression stroke (180° to 360°) : After the piston reaches the lower limit (bottom dead center) of its travel, it begins to move upward. As this happens, the inlet valve closes. The exhaust valve is also closed, so the cylinder is sealed. As the piston moves upward, the air-petrol mixture is compressed. Due to compression, the pressure and temperature are increased and is shown by the line BC on the P-V diagram.

As the piston reaches the top dead center of its travel on the compression stroke, an electric spark is produced at the spark plug. The ignition system delivers a high voltage surge of electricity to the spark plug to create spark. The spark ignites the air-petrol mixture and combustion takes place at constant volume as shown by the line CD in the PV diagram.

Power stroke (360° - 540°): The expansion of gases due to the heat of combustion exerts a pressure on the piston. Under this impulse, the piston moves from top dead center to bottom dead center and the power is transmitted to the crankshaft through the connecting rod. Both the inlet and exhaust values remain closed during this stroke. The expansion of the gas is shown by the curve DE.

Exhaust stroke (540° - 720°): During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The drop in pressure at constant volume is represented by the line EB. The piston moves from bottom dead center to top dead center and pushes the remaining gases to the atmosphere. When the piston reaches the top dead center the exhaust valve closes and cycle is completed. The line BA on the P-V diagram represents this stroke. The operations are repeated over and over again in running the engine.

Thus four strokes are completed in two revolutions (0-720°) of the crank shaft. i.e., one power stroke for every two revolutions of the crank shaft.

Four stroke cycle diesel engine

The four stroke cycle diesel engine operates on *diesel cycle* or *constant pressure cycle*. Since ignition in these engines is due to the temperature of the compressed air, they are also called *compression ignition engines*. The construction and working of the four stroke diesel engine is shown in fig. 7.6, and fig. 7.7 shows a theoretical diesel cycle. The four strokes are as follows.

Suction stroke (0 - 180°): During suction stroke, the piston is moved from the top dead center to the bottom dead center by the crankshaft. The crankshaft is revolved either by the momentum of the flywheel or by the power generated by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The fresh air is sucked into the cylinder due to the downward movement of the piston. The line AB on the P-V diagram represents this operation.

Compression stroke (180° - 360°): The air drawn at the atmospheric pressure during suction stroke is compressed to high pressure and temperature as piston moves from the bottom dead center to top dead center. This operation is represented by the curve BC on the P-V diagram. Just before the end of this stroke, a metered quantity of fuel is injected into the hot compressed air in the form of fine sprays by means of fuel injector. The fuel starts burning at constant pressure shown by the line CD. At point D, fuel supply is cut off. Both the inlet and exhaust valves remain closed during this stroke.

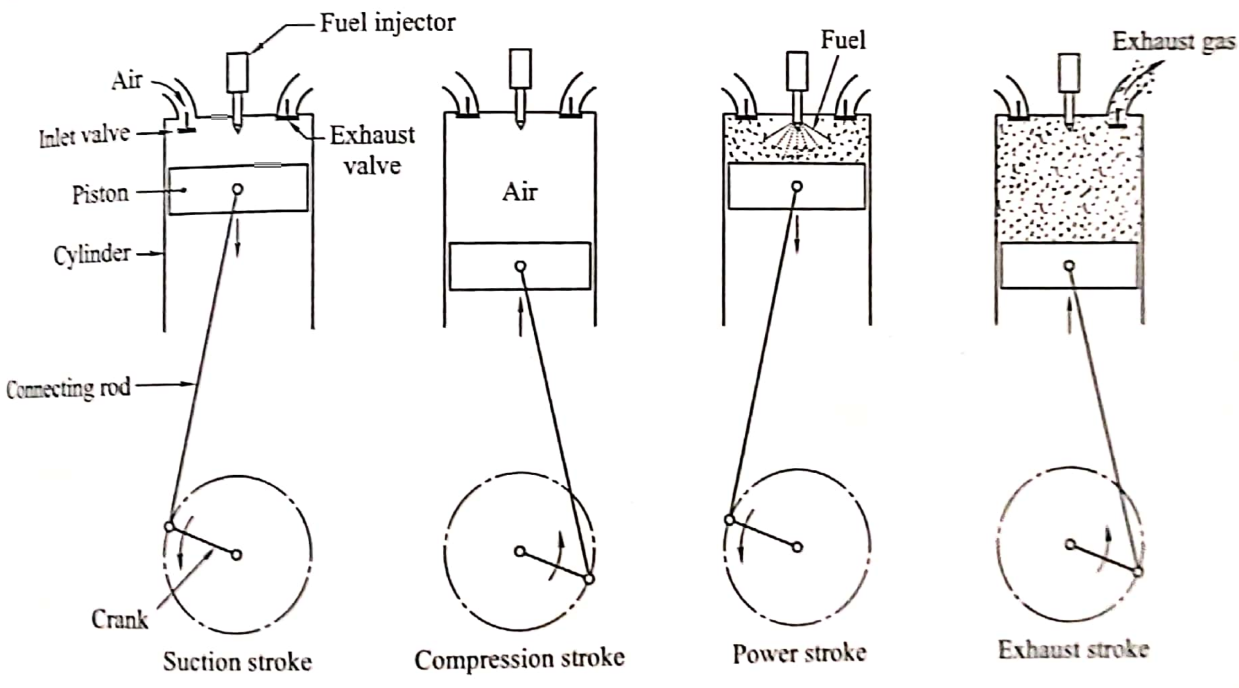

Fig. 7.6 Four stroke cycle diesel engine

Power stroke (360° - 540°): The expansion of gases due to the heat of combustion exerts a pressure on the piston. Under this impulse, the piston moves from top dead center to bottom dead center The impulse power is transmitted to the crank shaft through the piston and through the connecting rod. The crank shaft is rotated due to this force. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas is shown by the curve DE.

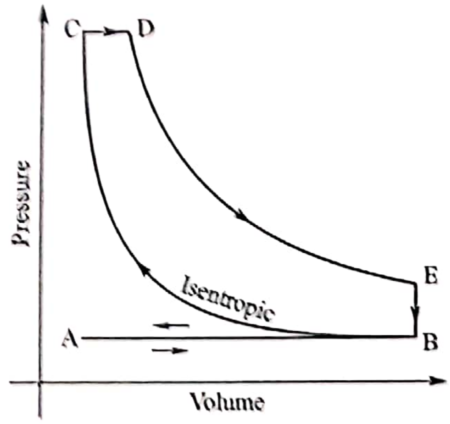

Fig. 7.7 Theoretical diesel cycle

Exhaust stroke (540° - 720°): During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escape because of their own expansion. The drop in pressure at constant volume is represented by the vertical line EB. The piston moves from bottom dead center to top dead center and pushes the remaining gases to the atmosphere. When the piston reaches the top dead center the exhaust valve closes and the cycle is completed. The line BA on the P-V diagram represents this stroke. Thus four strokes are completed in two revolutions of the crankshaft.

Two stroke cycle engine

In two stroke cycle engines, the suction and exhaust strokes are eliminated. There are only two remaining strokes i.e., the compression stroke and power stroke and these are usually called *upward stroke* and *downward stroke* respectively. Also, instead of valves, there are inlet and exhaust ports in two stroke cycle engines. The burnt exhaust gases are forced out through the exhaust port by a fresh charge, which enters the cylinder nearly at the end of the working stroke through the inlet port. The process of removing burnt exhaust gases from the engine cylinder is known as *scavenging*.

Two stroke cycle petrol engine

The principle of two stroke cycle petrol engine is shown in fig. 7.8. Its two strokes are described as follows:

Upward stroke (0 - 180°): During the upward stroke, the piston moves from bottom dead center to top dead center, compressing the air-petrol mixture in the cylinder. The cylinder is connected to a closed crank chamber. Due to upward movement of the piston, a partial vacuum is created in the crankcase, and a new charge is drawn into the crank case through the uncovered inlet port. The exhaust port and transfer port are covered when the piston is at the top dead center position as shown in fig. 7.8b. The compressed charge is ignited in the combustion chamber by a spark provided by the spark plug.

Downward stroke (180° - 360°): As soon as the charge is ignited, the hot gases force the piston to move downwards, rotating the crankshaft, thus doing the useful work. During this

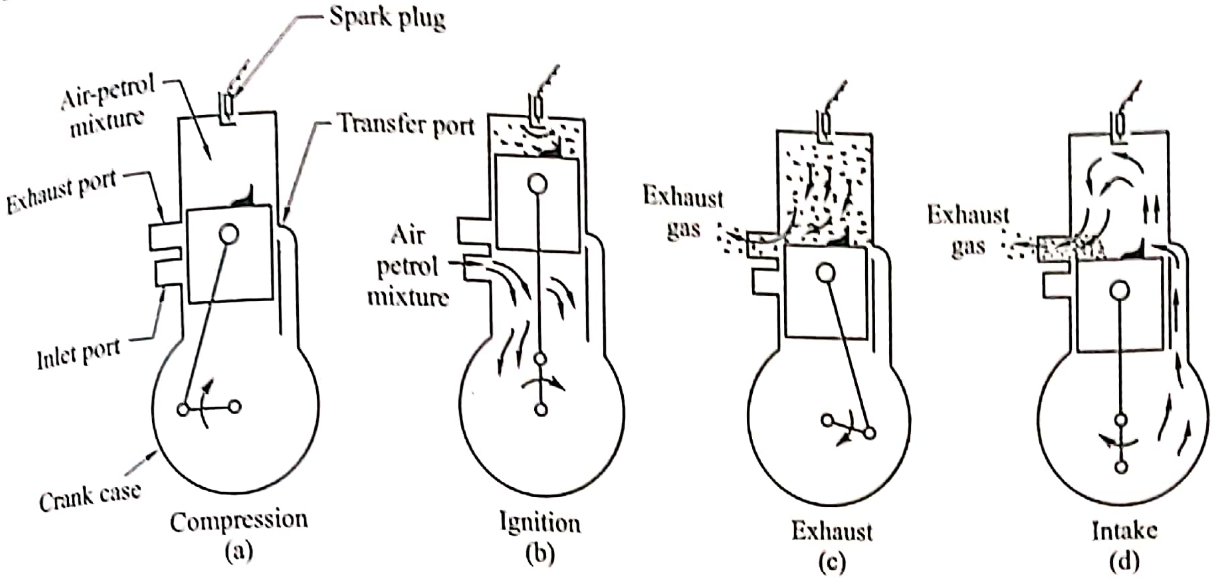

Fig. 7.8 Two stroke cycle petrol engine

stroke the inlet port is covered by the piston and the new charge is compressed in the crank case as shown in the fig. 7.8c. Further downward movement of the piston uncovers first the exhaust port and then the transfer port as shown in fig. 7.8d. The burnt gases escape through the exhaust port. As soon as the transfer port opens, the compressed charge from the crankcase flows into the cylinder. The charge is deflected upwards by the hump provided on the head of the piston and pushes out most of the exhaust gases. It may be noted that the incoming air-petrol mixture helps the removal of burnt gases from the engine cylinder. If in case these exhaust gases do not leave the cylinder, the fresh charge gets diluted and efficiency of the engine will decrease. The cycle of events is then repeated. Thus two strokes are completed in one revolution of the crankshaft.

Two stroke cycle diesel engine

The principle of two stroke cycle diesel engine is shown in fig. 7.9. Its two strokes are described as follows:

Upward stroke (0 - 180°): During the upward stroke, the piston moves from bottom dead center to top dead center, compressing the air in the cylinder. The cylinder is connected to a closed crank chamber. Due to upward movement of the piston, a partial vacuum is created in the crankcase, and fresh air is drawn into the crank case through the uncovered inlet port. The exhaust port and transfer port are covered when the piston is at the top dead center position as shown in fig. 7.9b. Just before the end of this stroke, a metered quantity of fuel is injected into cylinder and ignited by the hot compressed air.

Downward stroke (180° - 360°): As soon as the charge is ignited, the hot gases force the piston to move downwards, rotating the crankshaft, thus doing the useful work. During this stroke the inlet port is covered by the piston and fresh air is compressed in the crank case as shown in the fig. 7.9c. Further downward movement of the piston uncovers first the exhaust port and then the transfer port as shown in fig. 7.9d. The burnt gases escape through the exhaust port. As soon as the transfer port opens, the compressed air from the crankcase flows into the cylinder. The air is deflected upwards by the hump provided on the head of

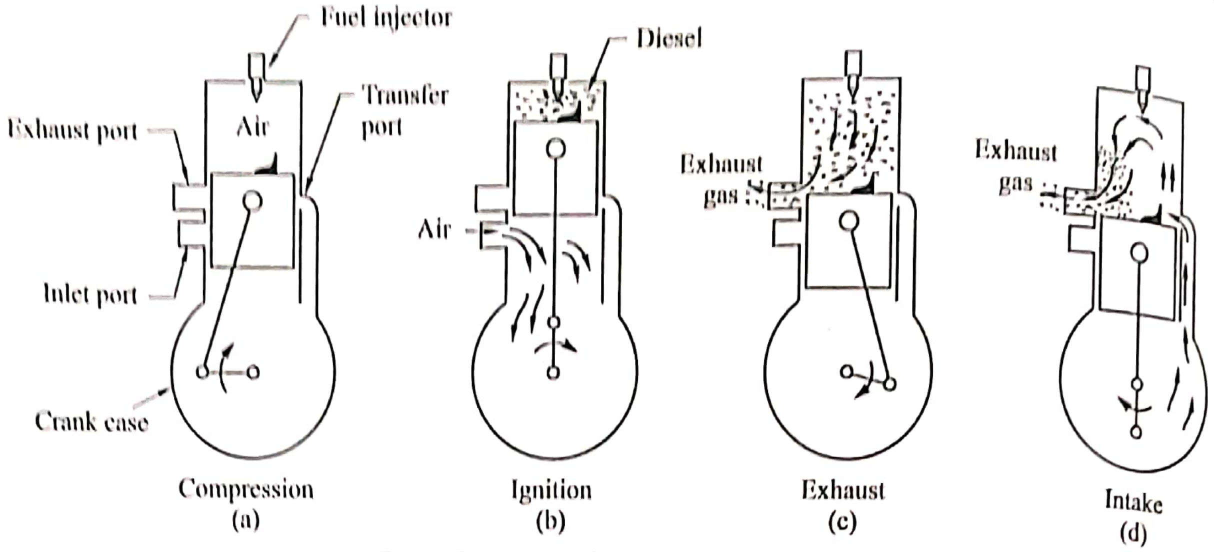

Fig. 7.9 Two stroke cycle diesel engine

the piston and pushes out most of the exhaust gases. It may be noted that the incoming air helps the removal of burnt gases from the engine cylinder. The cycle of events is then repeated. Thus two strokes are completed in one revolution of the crankshaft.

Comparison between petrol engine and diesel engine

Petrol engine	*Diesel engine*
1. It works on Otto cycle.	It works on diesel cycle.
2. Air and petrol are mixed in the carburetor before they enter into the cylinder.	Diesel is fed into the cylinder by fuel injection and is mixed with air inside the cylinder.
3. It compresses a mixture of air and petrol and is ignited by an electric spark (spark ignition).	It compresses only air and ignition is accomplished by the heat of compression. (compression ignition).
4. Cylinder is fitted with a spark plug.	Cylinder is fitted with a fuel injector.
5. Less thermal efficiency and more fuel consumption.	More thermal efficiency and less fuel consumption.
6. Compression ratio ranges from 4:1 to 10:1.	Compression ratio ranges from 12:1 to 22:1.
7. Less initial cost and more running cost.	More initial cost and less running cost.
8. Light weight and occupy less space.	Heavy and occupies more space.
9. Easy to start even in cold weather.	Difficult to start in cold weather and requires heater plugs.
10. Requires frequent overhauling.	They run for longer periods between overhauls.
11. Fuel (petrol) is expensive and more volatile.	Fuel (diesel) is cheaper and less volatile.
12. Used in light vehicles like cars, motor cycles, scooters, etc.	Used in heavy duty vehicles like tractors, trucks, buses, locomotives, etc.

Comparison between four stroke and two stroke cycle engines

Four stroke cycle engine	Two stroke cycle engines
1. One working stroke for every two revolutions of the crankshaft.	One working stroke for each revolution of the crankshaft.
2. Turning moment on the crank shaft is not even, hence heavier flywheel is required.	Turning moment on the crankshaft is more even, hence lighter flywheel is required
3. More output due to full fresh charge intake and full burnt gases exhaust	Less output due to mixing of fresh charge with the burnt gases.
4. Less fuel consumption	More fuel consumption
5. Higher thermal efficiency	Lower thermal efficiency
6. Engine design is complicated	Engine design is simple
7. Lesser rate of wear and tear	Greater rate of wear and tear
8. It has inlet and exhaust valves	It has inlet and exhaust ports
9. Engine is heavy and bulky	For the same power, the engine is light and compact
10. It requires lesser coolant and lubricant	It requires greater coolant and lubricant.
11. Complicated lubricating system	Simple lubricating system
12. More initial cost	Less initial cost
13. Less running noise	More running noise
14. Engine cannot run in either direction	Engine can be easily reversed if it is of valve less type
15. Used in cars, buses, trucks, tractors, etc.	Used in lawn movers, motor cycles, scooters, etc.

Mean effective pressure

Mean effective pressure is the mean pressure acting on the piston throughout the power stroke.

Let A = Area of indicator diagram in m^2

b = Base width of indicator diagram in m

k = Spring value of the spring used in the indicator in bar/m

$\therefore$ Actual mean effective pressure $p_{mi} = \dfrac{Ak}{b}$ bar $\quad (1 \text{ bar} = 10^5 \text{ Pa} = 10^5 \text{ N/m}^2)$

Indicated power

The power developed in the cylinder of an engine is known as *indicated power IP*.

Let p_{mi} = Indicated mean effective pressure in bar $\quad (1 \text{ bar} = 10^5 \text{ N/m}^2)$

a = Area of cylinder in $m^2 = \dfrac{\pi}{4} d^2$

d = Diameter of cylinder (bore) in m
l = Length of stroke in m
n = Speed of the crank shaft in rpm
n' = Speed of the crankshaft in rps = $n/60$
N = Number of cycles per second = n' for two stroke engine
= $\frac{n'}{2}$ for four stroke engine
i = Number of cylinders

Force acting on the piston $= 10^5 p_{mi} \times a$ N

Work done during working stroke $= 10^5 p_{mi} al$ Nm

Work done per second for one cylinder $= 10^5 p_{mi} alN$ Nm/s

$\therefore$ Indicated power per cylinder $IP = \frac{10^5 p_{mi} alN}{10^3} = 100 p_{mi} alN$ kW

For i cylinders, indicated power $IP = 100\, i p_{mi}\, alN$ kW

$= \frac{i\, p_{mi}\, alN}{1000}$ kW ... if p_{mi} is in N/m² (Pa)

Brake power: The power developed by an engine at the output shaft is called the *brake power BP.*

Let T = Braking torque in Nm
n' = Speed in rps
ω = Angular speed in rad/s = $2\pi n'$

$\therefore$ Brake power $BP = \frac{T\omega}{1000}$ kW $= \frac{2\pi n' T}{1000}$ kW

Also, brake power $BP = 100\, i p_{mb}\, alN$ kW

where p_{mb} = Brake mean effective pressure in bar

The resisting torque on the engine output shaft can be measured by using belt or rope or prony brake dynamometer.

Belt dynamometer: *(refer fig. 7.10)*

Torque $T = (T_1 - T_2) R$

where T_1 = Tight side tension in belt in N
T_2 = Slack side tension in belt in N
R = Effective radius of pulley in m = $\frac{D_b + d_r}{2}$
D_b = Diameter of the drum in m
d_r = Diameter of the rope in m

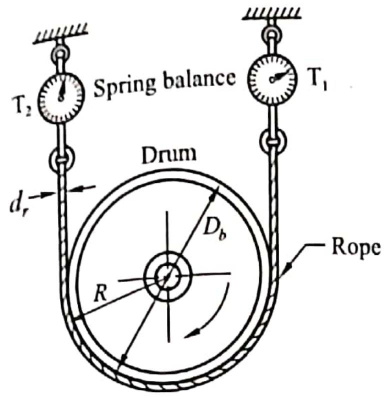

Fig. 7.10 *Belt dynamometer*

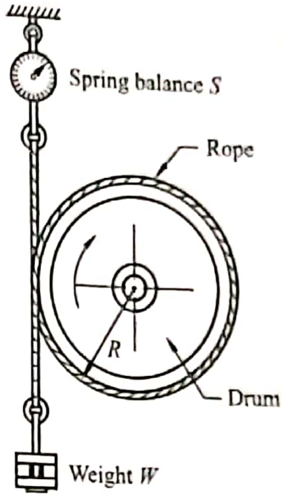

Fig. 7.11 *Rope brake dynamometer*

Rope brake dynamometer: *(refer fig. 7.11)*

Torque $T = (W-S)R$

where W = Suspended weight in N

S = Spring balance reading in N

R = Effective radius of pulley measured to the center of the rope in m

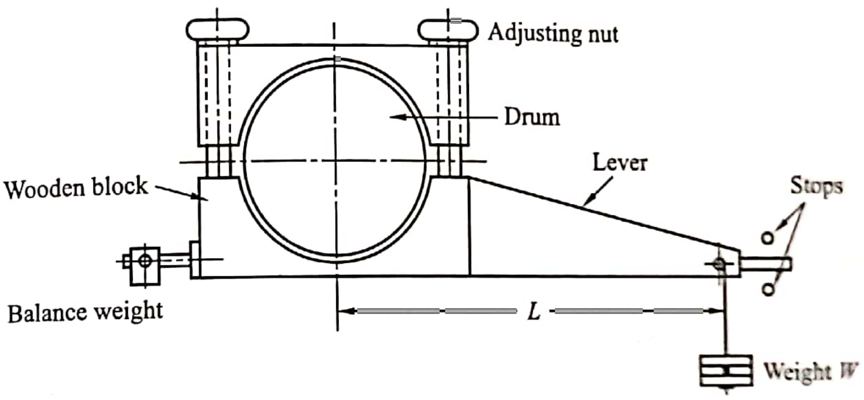

Fig. 7.12 *Prony brake*

Prony brake: *(refer fig. 7.12)*

Torque $T = WL$

where W = Weight at the end of lever in N

L = Effective length of lever in m

Friction power

The amount of power lost in friction is the *friction power FP*. It is the difference between indicated power and brake power.

$\therefore \quad FP = IP - BP$

Mechanical efficiency

Mechanical efficiency is defined as the ratio of brake power to the indicated power.

Mechanical efficiency $\eta_m = \dfrac{BP}{IP} = \dfrac{BP}{BP+FP}$

or $\eta_m = \dfrac{\text{Brake mean effective pressure } p_{mb}}{\text{Indicated mean effective pressure } p_{mi}}$

Indicated thermal efficiency

It is the ratio of the indicated power to the energy supplied by the fuel.

Let IP = Indicated power in kW

m = Mass of the fuel used in kg/s

c = Calorific value of fuel in kJ/kg

$\therefore$ Indicated thermal efficiency $\eta_i = \dfrac{IP}{m \times c}$

The value $\dfrac{3600m}{IP}$ in kg/kW-h is called *specific fuel consumption* on indicated power basis.

If Q is the flow rate of the fuel in lit/s and ρ is the specific gravity of fuel then,

Mass of fuel used $m = Q \times \rho$

Brake thermal efficiency

It is the ratio of brake power to the energy supplied by the fuel.

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c}$

The value $\dfrac{3600m}{BP}$ in kg/kW-h is called *specific fuel consumption* on brake power basis.

Example 1: The following data are collected from a four - stroke, single cylinder oil engine running at full load. Bore 200 mm, stroke 280 mm, speed 300 rpm, indicated mean effective pressure 5.6 bar, torque on the brake drum 250 N m, oil consumed 4.2 kg/h, calorific value of oil used 41000 kJ/kg. Determine the mechanical efficiency, indicated thermal efficiency, and brake thermal efficiency. (VTU, Jan 2017)

Data: $i = 1$, $d = 200\text{ mm} = 0.2\text{m}$, $l = 280\text{ mm} = 0.28\text{ m}$, $n = 300\text{ rpm}$, $n' = \dfrac{300}{60} = 5\text{ rps}$,

$N = \dfrac{n'}{2} = \dfrac{5}{2} = 2.5$ cycles/s (4-stroke), $p_{mi} = 5.6$ bar, $m = 4.2\text{ kg/h} = \dfrac{4.2}{3600}$ kg/s,

$T = 250$ Nm, $c = 41000$ kJ/kg

Solution: Area of piston $a = \dfrac{\pi}{4} d^2 = \dfrac{\pi}{4} \times 0.2^2 = 0.01\,\pi\text{ m}^2$

Indicated power $IP = 100\, i\, p_{mi}\, a\, l\, N$

$$= 100 \times 1 \times 5.6 \times 0.01\, \pi \times 0.28 \times 2.5 = 12.315\,\text{kW}$$

Brake power $BP = \dfrac{2\pi\, n' T}{1000} = \dfrac{2\pi \times 5 \times 250}{1000} = 7.854\,\text{kW}$

Mechanical efficiency $\eta_m = \dfrac{BP}{IP} = \dfrac{7.854}{12.315} = 0.638 = \mathbf{63.8\,\%}$

Indicated thermal efficiency $\eta_i = \dfrac{IP}{m \times c} = \dfrac{12.315 \times 3600}{4.2 \times 41000} = 0.257 = \mathbf{25.7\,\%}$

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c} = \dfrac{7.854 \times 3600}{4.2 \times 41000} = 0.164 = \mathbf{16.4\%}$

Example 2: A four stroke diesel engine has a piston diameter 250 mm and stroke 400 mm. The mean effective pressure is 4 bar and the speed is 500 rpm. The diameter of the brake drum is 1m and the effective brake load is 400N. Find indicated power, brake power and friction power. (VTU, Jan 2018)

Data: $d = 250\text{mm} = 0.25\text{m}$, $l = 400\text{ mm} = 0.4\text{ m}$, $p_m = 4\text{ bar}$, $n = 500\text{ rpm}$, $n' = (500/60)\text{ rps}$, $N = n'/2$ cycles/s (4-stroke), $D = 1\text{m}$, $R = 0.5\text{ m}$, $T_1 - T_2 = 400\text{ N}$

Solution:

Assume the engine is of single cylinder, $i = 1$

Torque on brake drum $T = (T_1 - T_2) R$

$$= 400 \times 0.5 = 200\text{ Nm}$$

Brake power $BP = \dfrac{2\pi n' T}{1000}$

$$= 2\pi \times \frac{500}{60} \times \frac{200}{1000} = \mathbf{10.472\ kW}$$

Indicated power $IP = 100\, i\, p_m\, a\, l\, N$

$$= 100 \times 1 \times 4 \times \left(\frac{\pi}{4} \times 0.25^2\right) \times 0.4 \times \frac{500}{60 \times 2}$$

$$= \mathbf{32.725\ kW}$$

Friction power $FP = IP - BP = 32.725 - 10.472 = \mathbf{22.253\ kW}$

Example 3: The following data were recorded during testing of a four stroke cycle engine. Area of the indicator diagram 580 mm^2, length of indicator diagram 75 mm, spring value 900 bar/m, cylinder diameter 200 mm, stroke 400 mm, and number of explosions per minute is 110. Determine,

(i) Indicated mean effective pressure, and

(ii) Indicated power

Data: $A = 580 \text{ mm}^2 = 580 \times 10^{-6} \text{ m}^2$, $b = 75 \text{ mm} = 0.75 \text{ m}$, $k = 900$ bar/m,

$d = 200 \text{ mm} = 0.2 \text{ m}$, $l = 400 \text{ mm} = 0.4 \text{ m}$, $N = \dfrac{110}{60}$ explosions per s (cycles/s)

Solution:

Assume the number of cylinder $i = 1$

Indicated mean effective pressure $p_m = \dfrac{Ak}{b} = \dfrac{580 \times 10^{-6} \times 900}{0.075} = 6.96$ bar

Area of piston $a = \dfrac{\pi}{4} d^2 = \dfrac{\pi}{4} \times 0.2^2 = 0.0314 \text{ m}^2$

Indicated power $IP = 100\, i p_m a l N$

$$= 100 \times 1 \times 6.96 \times 0.0314 \times 0.4 \times \frac{110}{60} = 16.03 \text{ kW}$$

Example 4: The following observations refer to a trial of a single cylinder diesel engine:

Brake power = 75 kW

Brake thermal efficiency = 35 %

Mechanical efficiency = 90%

Calorific value of oil used = 40000 kJ/kg

Determine: (i) Indicated power, (ii) Friction power, and (iii) Fuel consumption per brake power hour.

Data: $i = 1$, $BP = 75$ kW, $\eta_b = 35\% = 0.35$, $\eta_m = 90\% = 0.9$, $c = 40000$ kJ/kg

Solution:

Mechanical efficiency $\eta_m = \dfrac{BP}{IP}$

∴ Indicated power $IP = \dfrac{BP}{\eta_m} = \dfrac{75}{0.9} = 83.33$ kW

Friction power $FP = IP - BP$

$= 83.33 - 75 = 8.33$ kW

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c}$

i.e., $0.35 = \dfrac{75}{m \times 40000}$

$\therefore$ Mass flow of the fuel $\quad m = 5.357 \times 10^{-3}$ kg/s

$$= 5.357 \times 10^{-3} \times 3600 = 19.2852 \text{ kg/h}$$

Fuel consumption per BP hour $= \dfrac{m}{BP} = \dfrac{19.2852}{75} = \mathbf{0.257\ kg/kWh}$

Example 5: The following results refer to a test on a petrol engine:

Indicated power = 40 kW

Brake power = 35 kW

Fuel consumption per brake power hour = 0.3 kg

Calorific value of fuel = 44000 kJ/kg

Calculate mechanical, brake thermal, and indicated thermal efficiencies.

Data: $IP = 40$ kW, $BP = 35$ kW, $c = 44000$ kJ/kg, fuel consumption = 0.3 kg/kWh

Solution:

Fuel consumption $\quad m = 0.3 \times 35 = 10.5 \text{ kg/h} = \dfrac{10.5}{3600}$ kg/s

Mechanical efficiency $\quad \eta_m = \dfrac{BP}{IP} = \dfrac{35}{40} = 0.875 = \mathbf{87.5\ \%}$

Brake thermal efficiency $\quad \eta_b = \dfrac{BP}{m \times c}$

$$= \frac{35 \times 3600}{10.5 \times 44000} = 0.2727 = \mathbf{27.27\ \%}$$

Indicated thermal efficiency $\quad \eta_i = \dfrac{IP}{m \times c}$

$$= \frac{40 \times 3600}{10.5 \times 44000} = 0.3117 = \mathbf{31.17\ \%}$$

Example 6: A single cylinder four-stroke engine has bore of 180 mm, stroke of 200 mm and runs at 300 rpm. The torque on the brake drum is 200 Nm and the mean effective pressure is 6 bar. The fuel consumption is 4 kg/h. The calorific value of fuel is 42000 kJ/kg. Determine: brake power, indicated power, brake thermal efficiency, indicated thermal efficiency and mechanical efficiency. (VTU, Dec. 2011)

Data: $i = 1$, $d = 180$ mm $= 0.18$ m, $l = 200$ mm $= 0.2$ m, $n = 300$ rpm,

$n' = \dfrac{n}{60} = \dfrac{300}{60} = 5$ rps, $N = \dfrac{n'}{2} = \dfrac{5}{2} = 2.5$ cycles/s (4-stroke), $T = 200$ Nm, $p_{mi} = 6$ bar,

$m = 4 \text{ kg/h} = \dfrac{4}{3600}$ kg/s, $c = 42000$ kJ/kg

Solution:

$$\text{Brake power} \quad BP = \frac{2\pi\, n'T}{1000} = \frac{2\pi \times 5 \times 200}{1000} = \mathbf{6.283\ kW}$$

$$\text{Indicated power} \quad IP = 100\, i\, p_{mi}\, a l N$$

$$= 100 \times 1 \times 6 \times \left(\frac{\pi}{4} \times 0.180^2\right) \times 0.2 \times 2.5 = \mathbf{7.634\ kW}$$

$$\text{Brake thermal efficiency } \eta_b = \frac{BP}{m \times c} = \frac{6.283 \times 3600}{4 \times 42000} = 0.1346 = \mathbf{13.46\%}$$

$$\text{Indicated thermal efficiency } \eta_i = \frac{IP}{m \times c} = \frac{7.634 \times 3600}{4 \times 42000} = 0.1636 = \mathbf{16.36\%}$$

$$\text{Mechanical efficiency } \eta_m = \frac{BP}{IP} = \frac{6.283}{7.634} = 0.823 = \mathbf{82.3\%}$$

Example 7: A single cylinder four-stroke IC engine has a swept volume of 6 liters and runs at a rated speed of 300 rpm. The tensions on the tight side and stack side of the dynamometer belt is 700 N and 300 N respectively. The diameter of the dynamometer pulley is 1 m. The fuel consumption is 4 kg/h, the indicated mean effective pressure is 6 bar and the calorific value of the fuel is 42000 kJ/kg. Calculate brake power, indicated power, mechanical efficiency, indicated thermal efficiency, brake thermal efficiency and brake specific fuel consumption.

(VTU, July 2009)

Data: $i = 1$, 4-stroke, $V_s = a \times l = 6 \text{ liters} = 6 \times 10^{-3}\ \text{m}^3$, $n = 300$ rpm, $n' = \dfrac{300}{60} = 5$ rps,

$$N = \frac{n'}{2} = \frac{5}{2} = 2.5 \text{ cycles/s (4-stroke)},\ T_1 = 700\ \text{N},\ T_2 = 300\ \text{N},\ D = 1\ \text{m},$$

$$m = 4\ \text{kg/h} = \frac{4}{3600}\ \text{kg/s},\ p_{mi} = 6\ \text{bar},\ c = 42000\ \text{kJ/kg}$$

Solution:

$$\text{Torque} \quad T = (T_1 - T_2)R = (T_1 - T_2)\frac{D}{2}$$

$$= (700 - 300) \times \frac{1}{2} = 200\ \text{Nm}$$

$$\text{Brake power} \quad BP = \frac{2\pi\, n'T}{1000}$$

$$= \frac{2\pi \times 5 \times 200}{1000} = \mathbf{6.283\ kW}$$

Indicated power $IP = 100\, i\, p_{mi}\, (al)\, N$

$= 100 \times 1 \times 6 \times 6 \times 10^{-3} \times 2.5 = 9 \text{ kW}$

Mechanical efficiency $\eta_m = \dfrac{BP}{IP} = \dfrac{6.283}{9} = 0.698 = \mathbf{69.8\%}$

Indicated thermal efficiency $\eta_i = \dfrac{IP}{m \times c} = \dfrac{9 \times 3600}{4 \times 42000} = 0.1928 = \mathbf{19.28\%}$

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c} = \dfrac{6.283 \times 3600}{4 \times 42000} = 0.1346 = \mathbf{13.46\%}$

Specific fuel consumption on brake power basis $= \dfrac{3600\,m}{BP}$

$= \dfrac{3600 \times 4}{3600 \times 6.283} = \mathbf{0.6366 \text{ kg/kW-h}}$

Example 8: A single cylinder, two stroke oil engine is running at 450 rpm. Observations from a rope brake dynamometer are:

Diameter of the brake drum = 600 mm

Diameter of the rope = 20 mm

Load on the rope = 200 N

Spring balance reading = 30 N

Determine the brake power of the engine.

Data: $i = 1$, $n = 450$ rpm, $n' = \dfrac{450}{60} = 7.5$ rps, $D_b = 600$ mm $= 0.6$ m,

$d_r = 20$ mm $= 0.2$ m., $W = 200$ N, $S = 30$ N

Solution:

Effective radius of brake drum $R = \dfrac{D_b + d_r}{2}$

$= \dfrac{0.6 + 0.02}{2} = 0.31 \text{ m}$

Torque on the drum $T = (W - S) \times R$

$= (200 - 30) \times 0.31 = 52.7 \text{ Nm}$

Brake power $BP = \dfrac{2\pi\, n' T}{1000}$

$= \dfrac{2\pi \times 7.5 \times 52.7}{1000} = \mathbf{2.483 \text{ kW}}$

Example 9 : The following observations were recorded during a test on a 4-stroke engine. Bore = 250 mm, Stroke = 400 mm, Crank speed = 250 rpm, Net load on the brake drum = 700 N, Diameter of the brake drum = 2 m, Indicated mean effective pressure = 6 bar, Fuel consumption = 0.1 lit/min, Specific gravity of fuel = 0.78, Calorific value of fuel = 43900 kJ/kg. Determine (i) Brake power, (ii) Indicated power, (iii) Friction power, (iv) Mechanical efficiency and (v) Indicated and brake thermal efficiency. (VTU, Jan 2018)

Data: $d=250=0.25\text{ m},\ l=400\text{ mm}=0.4\text{ m},\ n=250\text{ rpm},\ n'=\dfrac{n}{60}=\dfrac{250}{60}\text{ rps},$

$N=\dfrac{n'}{2}$ cycles/s (4-stroke), $T_1-T_2=700\text{ N},\ D=2\text{ m},\ R=1\text{ m},\ p_{mi}=6\text{ bar},$

$Q=0.1\text{ lit/min}=0.1/60\text{ lit/s},\ \rho=0.78,\ c=43900\text{ kJ/kg}$

Solution:

Assume the engine is of single cylinder, $i=1$

Torque on the brake drum $T=(T_1-T_1)R=700\times 1=700\text{ Nm}$

Brake power $$BP=\frac{2\pi n'T}{1000}$$

$$=2\pi\times\frac{250}{60}\times\frac{700}{1000}=18.326\text{ kW}$$

Indicated power $$IP=100\,i p_{mi}\,a\,l\,N$$

$$=100\times 1\times 6\times\frac{\pi}{4}\times 0.25^2\times 0.4\times\frac{250}{60\times 2}$$

$$=\mathbf{24.544\text{ kW}}$$

Friction power $$FP=IP-BP=24.544-18.326=\mathbf{6.218\text{ kW}}$$

Mechanical efficiency $$\eta_m=\frac{BP}{IP}=\frac{18.326}{24.544}=0.7467=\mathbf{74.67\%}$$

Mass of fuel used $$m=Q\rho=\frac{0.1}{60}\times 0.78=1.3\times 10^{-3}\text{ kg/s}$$

Indicated thermal efficiency $$\eta_i=\frac{IP}{m\times c}=\frac{24.544}{0.0013\times 43900}=0.43=\mathbf{43\%}$$

Brake thermal efficiency $$\eta_b=\frac{BP}{m\times c}$$

$$=\frac{18.326}{0.0013\times 43900}=0.321=\mathbf{32.1\%}$$

Example 10 : The following are the details of 4-stroke petrol engine: (i) Diameter of brake drum = 600.3 mm, (ii) Full brake load on drum = 250 N, (iii) Brake drum speed = 450 rpm.

(iv) Calorific value of petrol = 40 MJ/kg, (v) Brake thermal efficiency = 32%, (vi) Mechanical efficiency = 80%, (vii) Specific gravity of petrol = 0.82. Determine: (a) Brake power, (b) Indicated power, (c) Fuel consumption in liters per second and (d) Indicated thermal efficiency.

(VTU, Jan 2004)

Data: $D = 600.3\ \text{mm} = 0.6003\ \text{m},\ R = 0.30015\ \text{m},\ T_1 - T_2 = 250\ \text{N},\ n = 450\ \text{rpm},$

$n' = \dfrac{450}{60} = 7.5\ \text{rps},\ N = \dfrac{n'}{2} = \dfrac{7.5}{2} = 3.75\ \text{cycles/s (4-stroke)},\ c = 40\ \text{MJ/kg} = 40 \times 10^3\ \text{kJ/kg},$

$\eta_b = 32\% = 0.32,\ \eta_m = 80\% = 0.8,\ \rho = 0.82$

Solution:

Assuming the petrol engine is of single cylinder, i.e., $i = 1$

Torque on the brake drum $\quad T = (T_1 - T_2)R = 250 \times 0.30015$

$= 75.0375\ \text{N m}$

Brake power $\quad BP = \dfrac{2\pi n'T}{1000} = \dfrac{2\pi \times 7.5 \times 75.0375}{1000} = \mathbf{3.536\ kW}$

Mechanical efficiency $\quad \eta_m = \dfrac{BP}{IP}$

∴ Indicated power $\quad IP = \dfrac{BP}{\eta_m} = \dfrac{3.536}{0.8} = \mathbf{4.42\ kW}$

Brake thermal efficiency $\quad \eta_b = \dfrac{BP}{m \times c}$

i.e., $\quad 0.32 = \dfrac{3.536}{m \times 40 \times 10^3}$

∴ Mass flow of the fuel $\quad m = 2.7625 \times 10^{-4}\ \text{kg/s}$

Fuel consumption in lit/s $\quad Q = \dfrac{m}{\rho} = \dfrac{2.7625 \times 10^{-4}}{0.82} = \mathbf{3.369 \times 10^{-4}\ lit/s}$

Indicated thermal efficiency $\quad \eta_i = \dfrac{IP}{m \times c} = \dfrac{4.42}{2.7625 \times 10^{-4} \times 40 \times 10^3} = 0.4 = \mathbf{40\%}$

Example 11 : Calculate the brake power of a single cylinder four stroke petrol engine which is running at a speed of 400 rpm. The load on the brake drum is 24 kg and the spring balance reads 4 kg. The diameter of the brake drum is 600 mm and the rope diameter is 30 mm.

(VTU, Jan 2007)

Data: $i = 1, n = 400\ \text{rpm},\ n' = \dfrac{400}{60}\ \text{rps},\ W = 24\ \text{kg} = 24 \times 9.8066\ \text{N},\ S = 4\ \text{kg} = 4 \times 9.8066\ \text{N}$

$D_b = 600\ \text{m},\ d_r = 30\ \text{mm}$

Solution: *Refer fig. 7.11.*

Effective radius of the drum $R = \dfrac{D_b + d_r}{2} = \dfrac{600+30}{2} = 315 \text{ mm}$

Torque on the brake drum
$$T = (W-S)R$$
$$= (24-4)\times 9.8066 \times 315 = 61781.58 \text{ N mm}$$
$$= 61.782 \text{ N m}$$

Brake power
$$BP = \frac{2\pi n' T}{1000} = \frac{2\pi \times 400 \times 61.782}{60\times 1000}$$
$$= \mathbf{2.588 \text{ kW}}$$

Example 12: A four cylinder, four-stroke petrol engine 100 mm bore and 175 mm stroke was tested under a constant speed of 600 rpm.

Diameter of belt dynamometer pulley = 1 m

Tight side tension in the belt = 800 N

Slack side tension in the belt = 400 N

Determine the brake power and brake mean effective pressure.

Data: $i=4$, $d=100 \text{ mm} = 0.1 \text{ m.}$, $l = 175 \text{ mm} = 0.175 \text{ m}$, $n = 600 \text{ rpm}$, $n' = \dfrac{600}{60} = 10 \text{ rps}$,

$N = \dfrac{n'}{2} = \dfrac{10}{2} = 5 \text{ cycles/s (4-stroke)}$, $D = 1 \text{ m.}$, $T_1 = 800 \text{ N}$, $T_2 = 400 \text{ N}$

Solution:

Radius of dynamometer pulley $R = \dfrac{D}{2} = \dfrac{1}{2} = 0.5 \text{ m}$

Torque on the pulley
$$T = (T_1 - T_2)R$$
$$= (800-400)\times 0.5 = 200 \text{ Nm}$$

Brake power
$$BP = \frac{2\pi n' T}{1000}$$
$$= \frac{2\pi \times 10 \times 200}{1000} = \mathbf{12.566 \text{ kW}}$$

Area of cylinder
$$a = \frac{\pi}{4} d^2$$
$$= \frac{\pi}{4} \times 0.1^2 = 2.5 \times 10^{-3} \pi \text{ m}^2$$

also, brake power
$$BP = 100\, i\, p_{mb}\, a\, l\, N$$

i.e.,
$$12.566 = 100 \times 4 \times p_{mb} \times 2.5 \times 10^{-3} \pi \times 0.175 \times 5$$

$\therefore$ Brake mean effective pressure $p_{mb} = \mathbf{4.57 \text{ bar}}$

Example 13: A four cylinder, four stroke internal combustion engine develops an indicated power of 50 kW at 3000 rpm. The cylinder diameter is 75 mm and the stroke is 90 mm. Find the mean effective pressure in each cylinder. If the mechanical efficiency is 80%, what effective brake load would be required if the effective brake drum diameter is 0.6 m?

Data: $i = 4$, $IP = 50\,\text{kW}$, $n = 3000\,\text{rpm}$, $n' = \dfrac{3000}{60} = 50\,\text{rps}$, $N = \dfrac{n'}{2} = \dfrac{50}{2} = 25\,\text{cycles/s}$ (4-stroke), $d = 75\,\text{mm} = 0.075\,\text{m}$, $l = 90\,\text{mm} = 0.09\,\text{m}$, $\eta_m = 80\% = 0.8$, $D = 0.6\,\text{m}$

Solution:

Area of cylinder $\quad a = \dfrac{\pi}{4}d^2 = \dfrac{\pi}{4} \times 0.075^2 = 4.418 \times 10^{-3}\,\text{m}^2$

Indicated power $\quad IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $\quad 50 = 100 \times 4 \times p_{mi} \times 4.418 \times 10^{-3} \times 0.09 \times 25$

$\therefore$ Indicated mean effective pressure $\quad p_{mi} = 12.575\,\text{bar} = 12.575 \times 10^5\,\text{N/m}^2$

Mechanical efficiency $\quad \eta_m = \dfrac{BP}{IP}$

i.e., $\quad 0.8 = \dfrac{BP}{50}$

$\therefore$ Brake power $\quad BP = 40\,\text{kW}$

also, $\quad BP = \dfrac{2\pi\, n'\, T}{1000}$

i.e., $\quad 40 = \dfrac{2\pi \times 50 \times T}{1000}$

$\therefore$ Torque $\quad T = 127.32\,\text{Nm}$

also torque $\quad T = FR$

i.e., $\quad 127.32 = F \times \dfrac{0.6}{2}$

$\therefore$ Effective brake load $\quad F = \mathbf{424.4\,N}$

Example 14: A four cylinder four stroke petrol engine develops indicated power of 15 kW at 1000 rpm. The indicated mean effective pressure is 0.55 MPa. Calculate the bore and stroke of the piston if the length of stroke is 1.5 times the bore.

Data: $i = 4$, $IP = 15\,\text{kW}$, $n = 1000\,\text{rpm}$, $n' = \dfrac{1000}{60}$ rps, $N = \dfrac{n'}{2}$ (4-stroke), $l = 1.5d$,

$p_{mi} = 0.55\,\text{MPa} = 5.5\,\text{bar}$ $\quad (\because 1\,\text{MPa} = 10\,\text{bar})$

Solution:

Area of piston $a = \frac{\pi}{4} d^2$

Indicated power $IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $15 = 100 \times 4 \times 5.5 \times \frac{\pi}{4} \times d^2 \times 1.5\, d \times \frac{1000}{2 \times 60}$

or $d^3 = 6.945 \times 10^{-4}$

∴ The bore diameter $d = 0.0886\ \text{m} = \mathbf{88.6\ mm}$

Length of stroke $l = 1.5\, d$

$= 1.5 \times 88.6 = \mathbf{132.9\ mm}$

Example 15: A single cylinder four stroke petrol engine develops indicated power 7.5 kW. The mean effective pressure is 6.6 bar and the piston diameter is 100 mm. Calculate the average speed of the piston.

Data: $i = 1,\ N = \frac{n'}{2}$ (4-stroke), $IP = 7.5\ \text{kW},\ p_{mi} = 6.6\ \text{bar},\ d = 100\ \text{mm} = 0.1\ \text{m}$

Solution:

Area of piston $a = \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 0.1^2 = 0.007854\ \text{m}^2$

Indicated power $IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $7.5 = 100 \times 1 \times 6.6 \times 0.007854 \times l \times \frac{n'}{2}$

∴ $ln' = 2.894$

Velocity of piston $v = 2\, ln'$

$= 2 \times 2.894 = \mathbf{5.788\ m/s}$

Example 16: A single cylinder, four stroke diesel engine develops indicated power of 30 kW at 3000 rpm. The indicated mean effective pressure is 6.5 bar, and the piston speed is limited to 180 m/min. Determine the stroke and diameter of the cylinder. Also find the specific fuel consumption on brake power basis, if the mechanical efficiency is 80% and the indicated thermal efficiency is 30%. Take the calorific value of diesel as 40 MJ/kg.

(VTU, Jan 2008)

Data: $i = 1,\ IP = 30\ \text{kW},\ n = 3000\ \text{rpm},\ n' = \frac{3000}{60} = 50\ \text{rps},\ N = \frac{n'}{2} = \frac{50}{2} = 25\ \text{cycles/s}$ (4-stroke), $p_{mi} = 6.5\ \text{bar},\ v = 180\ \text{m/min} = \frac{180}{60} = 3\ \text{m/s},\ \eta_m = 80\% = 0.8,\ \eta_i = 30\% = 0.3,$

$c = 40\ \text{MJ/kg} = 40 \times 10^3\ \text{kJ/kg}$

Solution:

Velocity of piston $v = 2\,l n'$

i.e., $3 = 2 \times l \times 50$

$\therefore$ Stroke $l = \mathbf{0.03\ m}$

Area of cylinder $a = \dfrac{\pi}{4} d^2$

Indicated power $IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $30 = 100 \times 1 \times 6.5 \times \dfrac{\pi}{4} \times d^2 \times 0.03 \times 25$

$\therefore$ Diameter of cylinder $d = \mathbf{0.28\ m}$

Mechanical efficiency $\eta_m = \dfrac{\eta_b}{\eta_i}$

i.e., $0.8 = \dfrac{\eta_b}{0.3}$

$\therefore$ Brake thermal efficiency $\eta_b = 0.24$

also $\eta_b = \dfrac{BP}{m \times c}$

$\therefore$ Mass of fuel per second per brake power $= \dfrac{m}{BP} = \dfrac{1}{\eta_b \times c}$

$$= \frac{1}{0.24 \times 40 \times 10^3} = 1.0416 \times 10^{-4}\ \text{kg/kWs}$$

Specific fuel consumption $= \dfrac{3600 \times m}{BP}$

$$= 3600 \times 1.04167 \times 10^{-4} = \mathbf{0.375\ kg/kWh}$$

Example 17 : The indicated power of a four stroke petrol engine is 60 kW at a piston speed of 6 m/s. The diameter of a cylinder is 300 mm and the crank radius is 225 mm. Find the speed of the crank shaft in rpm and the mean effective pressure.

Data: $IP = 60$ kW, $v = 6$ m/s, $d = 300$ mm $= 0.3$ m, $r = 225$ mm $= 0.225$ m, $i = 1$, $N = \dfrac{n'}{2}$ (4-stroke)

Solution:

Stroke length $l = 2r = 2 \times 0.225 = 0.45$ m

Velocity of piston $v = 2\,l n'$

i.e., $6 = 2 \times 0.45 \times n'$

$\therefore$ Crank shaft speed $\quad n' = 6.667$ rps

or $\quad n = 6.667 \times 60 = \textbf{400 rpm}$

Area of piston $\quad a = \dfrac{\pi}{4} d^2 = \dfrac{\pi}{4} \times 0.3^2 = 0.0225\,\pi\,\text{m}^2$

Indicated power $\quad IP = 100\, i\, p_{mi}\, a l N$

i.e., $\quad 60 = 100 \times 1 \times p_{mi} \times 0.0225\,\pi \times 0.45 \times \dfrac{6.667}{2}$

$\therefore$ Indicated mean effective pressure $\quad p_{mi} = \textbf{5.659 bar}$

Example 18 : A four cylinder two-stroke petrol engine develops 30 kW at 2500 rpm. The mean effective pressure on each piston is 6 bar and mechanical efficiency is 80%. Calculate the diameter and stroke of each cylinder if the stroke to bore ratio is 1.5. Also calculate the fuel consumption, if the brake thermal efficiency is 28%. The calorific value of the fuel is 43900 kJ/kg. (VTU, July 2016)

Data: $i = 4$, $BP = 30$ kW, $n = 2500$ rpm, $n' = \dfrac{2500}{60}$ rps, $N = n' = \dfrac{2500}{60}$ cycles/s (2-stroke),

$p_{mi} = 8$ bar, $\eta_m = 80\% = 0.8$, $\dfrac{l}{d} = 1.5$, $l = 1.5\,d$, $\eta_b = 28\% = 0.28$, $c = 43900$ kJ/kg.

Solution:

Mechanical efficiency $\quad \eta_m = \dfrac{BP}{IP}$

$\therefore$ Indicated power $\quad IP = \dfrac{BP}{\eta_m} = \dfrac{30}{0.8} = 37.5$ kW

Also, $\quad IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $\quad 37.5 = 100 \times 4 \times 8 \times \dfrac{\pi}{4} d^2 \times 1.5\, d \times \dfrac{2500}{60}$

$\therefore$ Bore diameter $\quad d = 0.062\text{ m} = \textbf{62 mm}$

Stroke length $\quad l = 1.5\,d = 1.5 \times 62 = \textbf{93 mm}$

Brake thermal efficiency $\quad \eta_b = \dfrac{BP}{m \times c}$

$\therefore$ Mass of the fuel $\quad m = \dfrac{BP}{\eta_b c} = \dfrac{30}{0.28 \times 43900} = 2.4406 \times 10^{-3}$ kg/s

Specific fuel consumption on brake power basis $= \dfrac{3600\,m}{BP}$

$$= \frac{3600 \times 2.4406 \times 10^{-3}}{30} = \textbf{0.29287 kg/kWh}$$

Example 19: A person conducted a test on a single cylinder two-stroke petrol engine and found that the mechanical and brake thermal efficiencies of the engine were 0.7 and 0.2 respectively. The engine with a mean effective pressure of 6 bar runs at 300 rpm consuming fuel at a rate of 2.2 kg/hr. Given that the calorific value of the fuel as 42,500 kJ/kg and that the stroke to bore ratio of the engine cylinder is 1.2. Find the bore and stroke of the engine.

(VTU, Jan 2006)

Data: $i=1,\ \eta_m=0.7,\ \eta_b=0.2,\ p_m=6$ bar, $n=300$ rpm, $n'=\dfrac{300}{60}=5$ rps, $c=42500$ kJ/kg

$N=n'=5$ cycles/s (2-stroke), $m=2.2$ kg/hr $=\dfrac{2.2}{3600}$ kg/s, $\dfrac{l}{d}=1.2,\ l=1.2d,$

Solution:

Brake thermal efficiency $\qquad \eta_b = \dfrac{BP}{m \times c}$

i.e., $\qquad 0.2 = \dfrac{BP \times 3600}{2.2 \times 42500}$

$\therefore$ Brake power $\qquad BP = 5.1944$ kW

Mechanical efficiency $\qquad \eta_m = \dfrac{BP}{IP}$

$\therefore$ Indicated power $\qquad IP = \dfrac{BP}{\eta_m} = \dfrac{5.1944}{0.7} = 7.4206$ kW

Also $\qquad IP = 100\, i\, p_{mi}\, a\, l\, N$

i.e., $\qquad 7.4206 = 100 \times 1 \times 6 \times \dfrac{\pi}{4} d^2 \times 1.2\, d \times 5$

$\therefore$ Bore diameter $\qquad d = 0.13794$ m $=$ **137.94 mm**

Stroke $\qquad l = 1.2\,d = 1.2 \times 137.94 =$ **165.528 mm**

Example 20: A gas engine working on a four stroke cycle has a cylinder diameter 0.25 m and length of stroke 0.45 m and is running at 180 rpm. Its mechanical efficiency is 80% when the mean effective pressure is 6.5 bars. Find indicated power, brake power and friction power. What is the fuel consumption rate (kg/h) and brake specific fuel consumption (kg/kWh) if the energy content in the fuel is 42000kJ/kg and brake thermal efficiency is 25%?

(VTU, Jun 2008)

Data: $i=1,\ d=0.25$ m, $l=0.45$ m, $n=180$ rpm, $n'=180/60=3$ rps,

$N=n'/2=3/2=1.5$ cycles/s (4-stroke), $\eta_b=25\%=0.25,\ \eta_m=80\%=0.8,$

$p_m=6.5$ bars, $c=42000$ kJ/kg

Solution:

Area of piston $a = \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 0.25^2 = 0.015625\,\pi\,m^2$

Indicated power $IP = 100\, i p_m a l N$

$= 100 \times 1 \times 6.5 \times 0.015625 \times \pi \times 0.45 \times 1.5$

$= \mathbf{7.179\ kW}$

$\therefore$ Brake power $BP = \eta_m \times IP$

$= 0.8 \times 7.179 = \mathbf{5.7432\ kW}$

Friction power $FP = IP - BP$

$= 7.179 - 5.7432 = \mathbf{1.4358\ kW}$

Brake thermal efficiency $\eta_b = \frac{BP}{m \times c}$

i.e., $0.25 = \frac{5.7432}{m \times 42000}$

$\therefore$ Mass of fuel consumed $m = 5.4697 \times 10^{-4}$ kg/s

Mass of fuel consumed per hour $m = 3600 \times 5.4697 \times 10^{-4}$

$= \mathbf{1.969\ kg/h}$

Specific fuel consumption on brake power basis

$$= \frac{m}{BP} = \frac{1.969}{5.7432} = \mathbf{0.34286\ kg/kWh}$$

Example 21: A single cylinder 4-stroke IC engine has a volume of 6 liters and runs at 300 rpm. At full load, the tension in the tight side and slack side of dynamometer belt is 700N and 300 N respectively. The pulley diameter of the belt dynamometer is 1 m. The fuel consumed in one hour is 4 kg with a calorific value of 42000 kJ/kg. If the indicated mean effective pressure is 6 bar, calculate the indicated power, brake power, mechanical efficiency, indicated thermal efficiency, brake thermal efficiency and specific fuel consumption on brake power basis. (VTU, June 2009)

Data: $i = 1$, $al = 6$ liters $= 6000\ cm^3 = 6 \times 10^{-3} m^3$, $n = 300$ rpm, $n' = 300/60 = 5$ rps, $N = n'/2 = 5/2 = 2.5$ cycle/s (4-stroke), $T_1 = 700$ N, $T_2 = 300$ N, $D = 1$m, $R = 0.5$ m, $m = 4$kg/h $= 4/3600$ kg/s, $c = 42000$ kJ/kg, $p_m = 6$ bar

Solution:

Indicated power $IP = 100\, i p_m a l N$

$= 100 \times 1 \times 6 \times 6 \times 10^{-3} \times 2.5 = \mathbf{9\ kW}$

Torque absorbed by the dynamometer $T = (T_1 - T_2) R$

$= (700 - 300) \times 0.5 = 200$ Nm

Brake power $BP = \dfrac{2\pi n' T}{1000}$

$= \dfrac{2\pi \times 5 \times 200}{1000} = 6.283 \text{ kW}$

Mechanical efficiency $\eta_m = \dfrac{BP}{IP} = \dfrac{6.283}{9} = 0.698 = 69.8\ \%$

Indicated thermal efficiency $\eta_i = \dfrac{IP}{mc}$

$= \dfrac{9 \times 3600}{4 \times 42000} = 0.1928 = 19.28\ \%$

Brake thermal efficiency $\eta_b = \dfrac{BP}{mc}$

$= \dfrac{6.283 \times 3600}{4 \times 42000} = 0.1346 = 13.46\ \%$

Specific fuel consumption on brake power basis $= \dfrac{3600m}{BP}$

$= \dfrac{4}{6.283} = 0.6366 \text{ kg/kWh}$

Example 22: A four cylinder diesel engine has a bore of 0.1 m and stroke of 0.15 m runs with a piston speed of 10 m/s. The power developed by the engine is 20×10^3 kW/m^3 of cylinder volume. If the brake thermal efficiency is 40%, calorific value of fuel is 40 MJ/kg and the specific gravity of fuel is 0.9, calculate i) speed of the engine, ii) brake power and iii) fuel required in litre/s.

Data: $i=4$, $d=0.1$ m, $l=0.15$ m, $v=10$ m/s, $P=20\times 10^3$ kW/m^3, $\eta_b=40\%=0.4$, $c=40$ MJ/kg $=40\times 10^3$ kJ/kg, $\rho=0.9$

Solution:

Velocity of piston $v = 2ln'$

i.e., $10 = 2 \times 0.15 \times n'$

Speed of the engine $n' = 33.333$ rps $= 33.333 \times 60 = 2000$ rpm

Stroke volume of the cylinder $V_s = \dfrac{\pi}{4} d^2 l = \dfrac{\pi}{4} \times 0.1^2 \times 0.15 = 1.178 \times 10^{-3}$ m^3

Stroke volume of 4 cylinders $V = 4 \times 1.178 \times 10^{-3} = 4.712 \times 10^{-3}$ m^3

Brake power $BP = P \times V = 20 \times 10^3 \times 4.712 \times 10^{-3} = 94.24$ kW

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c}$

i.e., $0.4 = \dfrac{94.24}{m \times 40 \times 10^3}$

$\therefore$ Mass of fuel $m = 5.89 \times 10^{-3}$ kg/s

Fuel consumption in litre/s $= \dfrac{m}{\rho} = \dfrac{5.89 \times 10^{-3}}{0.9} = \mathbf{6.54 \times 10^{-3}}$

Example 23: A four-stroke, four cylinder petrol engine is running at 6000 rpm with the piston speed of 15 m/s. The brake mean effective pressure is 1000 kN/m², and stroke volume of the cylinder is 0.4 litre. The brake specific fuel consumption is 0.3 kg/kWh and the calorific value of fuel is 40 MJ/kg. Determine: i) Stroke, ii) Bore, iii) Brake power, iv) Fuel consumption and v) Brake thermal efficiency.

Data: $i=4$, 4-stroke, $n=6000$ rpm, $n' = \dfrac{6000}{60} = 100$ rpm, $N = \dfrac{n'}{2} = \dfrac{100}{2} = 50$ cycles/s,

$v = 15$ m/s, $p_{mb} = 1000\text{ kN/m}^2 = \dfrac{1000 \times 10^3}{10^5} = 10$ bar, $V_s = 0.4$ litre $= 0.4 \times 10^{-3}\text{ m}^3$,

$\dfrac{3600m}{BP} = 0.3$ kg/kWh, $c = 40$ MJ/kg $= 40 \times 10^3$ kJ/kg

Solution:

Velocity of piston $v = 2ln'$

i.e., $15 = 2 \times l \times 100$

Length of stroke $l = \mathbf{0.075\ m}$

Stroke volume $V_s = \dfrac{\pi}{4} d^2 l$

i.e., $0.4 \times 10^{-3} = \dfrac{\pi}{4} d^2 \times 0.075$

Bore $d = \mathbf{0.0824\ m}$

Brake power $BP = 100\, i\, p_{mb} (al) N = 100\, i\, p_{mb} V_s N$ $(\because al = V_s)$

$= 100 \times 4 \times 10 \times 0.4 \times 10^{-3} \times 50 = \mathbf{80\ kW}$

Specific fuel consumption on brake power basis $= \dfrac{3600m}{BP}$

i.e., $0.3 = \dfrac{3600m}{80}$

$\therefore$ Fuel consumption $m = 6.667 \times 10^{-3}$ kg/s $= 6.667 \times 10^{-3} \times 3600 = $ **24 kg/h**

Brake thermal efficiency $\eta_b = \dfrac{BP}{m \times c} = \dfrac{80}{6.667 \times 10^{-3} \times 40 \times 10^{3}} = 0.3 = $ **30%**

Example 24: A six cylinder four-stroke engine develops 50 kW of indicated power at mep of 700 kPa. The bore and stroke are 70 mm and 100 mm respectively. If the engine speed is 3700 rpm, find the average misfires per unit time. (VTU, July 2013)

Data: $i = 6$, 4-stroke engine, $IP = 50$ kW, $p_m = 700$ kPa $= 700 \times 10^3$ Pa $= \dfrac{700 \times 10^3}{10^5}$

$= 7$ bar, $d = 70$ mm $= 0.07$ m, $l = 100$ mm $= 0.1$ m, $n = 3700$ rpm, $n' = \dfrac{3700}{60}$ rps

Solution:

For 4-stroke engine, actual number of explosions/s $N_{act} = \dfrac{n'}{2} = \dfrac{3700}{2 \times 60} = 30.833$

Also, $IP = 100\, i\, p_{mi}\, a\, l\, N_{th}$

i.e., $50 = 100 \times 6 \times 7 \times \left(\dfrac{\pi}{4} \times 0.07^2\right) \times 0.1 \times N_{th}$

$\therefore$ Theoretical number of explosions/s $N_{th} = 30.933$

Number of misfires/s $= N_{th} - N_{act}$

$= 30.933 - 30.833 = 0.1$

or Number of misfires/hour $= 0.1 \times 3600 = $ **360**

Review questions

1. What is an internal combustion engine?
2. Differentiate between an internal combustion engine and an external combustion engine.
3. State the advantages of internal combustion engine over the external combustion engine.
4. How are I.C. engines classified?
5. What is a flywheel? State its function.
6. Define the following terms as applied to I.C. engines : bore, stroke, TDC, BDC, clearance volume, and compression ratio.
7. How does a two stroke cycle engine differ from a four stroke cycle engine?
8. With a neat sketch explain the working of a four stroke petrol engine.
9. With a neat sketch explain the working of a two stroke petrol engine.

10. Explain with a neat sketch the working of a four stroke diesel engine.
11. Explain with a neat sketch the working of a two stroke diesel engine.
12. With the help of P-V diagram, explain the operation of four stroke petrol engine. (VTU, Jan 2017)
13. Explain with P-V diagram, the working of a four stroke diesel engine. (VTU, Jan 2018)
14. Tabulate the merits and demerits of petrol engine over diesel engine.
15. Give four important differences between petrol engines and diesel engines. (VTU, Jan 2015)
16. Give the advantages of 2 stroke engine over four stroke engine. (VTU, Jan 2014)
17. Compare the merits and demerits of four stroke cycle engine over two stroke cycle engine.
18. Give examples of automobiles in which two stroke and four stroke cycle engines are used.
19. Define the following : Mean effective pressure, *IP, BP, FP,* mechanical efficiency, indicated thermal efficiency and brake thermal efficiency.
20. Determine the indicated power developed by a two cylinder, two stroke cycle diesel engine running at 1000 rpm, when the indicated mean effective pressure is 5.5 bar. The engine has a piston of 150 mm diameter and 200 mm stroke. [Ans.: 64.79 kW]
21. A four cylinder, four stroke diesel engine has a bore 250 mm and stroke 300 mm runs at 900 rpm. Determine the brake power if the brake mean effective pressure is 500 kPa. [Ans.: 220.89 kW]
22. A single cylinder two stroke I.C. engine is running at 500 rpm. The stroke is 1.5 times the bore and the diameter of the piston is 150 mm. Find the indicated power if the mean effective pressure is 0.9 MPa. Also find the brake power and mechanical efficiency if the friction power is 5 kW. [Ans.: 29.82 kW, 24.82 kW, 83.23%]
23. The following observations were made during a test on a two stroke cycle oil engine. Bore 200 mm, stroke 250 mm, speed 350 rpm, brake drum diameter 1.2 m, net brake load 450 N, mean effective pressure 2.8 bar, oil consumption 3.6 kg/hr, calorific value of oil is 41868 kJ kg. Determine (i) I.P., (ii) B.P., (iii) F.P., (iv) Mechanical efficiency, (v) Brake thermal efficiency, and (vi) Indicated thermal efficiency. [Ans.: 12.828 kW, 9.896 kW, 2.932 kW, 77.1%, 23.6%, 30.6%]
24. A single cylinder four stroke diesel engine gave the following while running on full load. Area of the indicator card 300 mm^2, length of diagram 40 mm, spring constant 1000 bar/m, speed 400 rpm, load on the brake 380 N, spring balance reading 50 N, diameter of the brake drum 1.2 m, fuel consumption 2.8 kg/hr, calorific value of fuel 40000 kJ/kg, diameter of the cylinder 160 mm and stroke 200 mm.

    Calculate: (i) Indicated mean effective pressure and I.P. (ii) B.P. and F.P. (iii) Mechanical, indicated thermal and brake thermal efficiencies.
    [Ans.: 7.5 bar, 10.05 kW, 8.29 kW, 1.76 kW, 82.5%, 32.3%, 26.66%]

25. A four stroke IC engine running at 450 rpm has a bore diameter of 100 mm and stroke length 120 mm. The indicator diagram details are: Area of the diagram = 400 mm^2. Length of indicator diagram = 65 mm, Spring value = 1 bar/mm. Calculate the indicated power of the engine. (VTU, Jan 2016)

26. The diameter of the brake drum of an engine running at 300 rpm. is 1m. The spring balance pull is 0.2 times the dead load. Find the dead load if the brake power is 15 kW. [Ans.: 1193.66 N]

27. A four stroke six cylinder gas engine with a stroke volume of 1.75×10^{-3} m^3 develops 21 kW at 500 rpm. The indicated mean effective pressure is 6 bar. Find I.P and braking torque on the brake drum and mechanical efficiency. [Ans.: 26.25 kW, 401 N-m, 80%]

28. A single cylinder 4-stroke IC engine has a bore of 180mm, stroke of 200 mm and a rated speed of 300 rpm. Torque on the brake drum is 200 Nm and mean effective pressure is 6 bar. It consumes 4 kg of fuel in one hour. The calorific value of the fuel is 42000 kJ/kg. Determine (i) brake power, (ii) indicated power, (iii) brake thermal efficiency and (iv) mechanical efficiency. (VTU, July 2003)

[Ans.: 6.283 kW, 7.634 kW, 13.46 %, 82.3%]

24. A single cylinder 4-stroke engine runs at 1000 rpm and has a bore of 115 mm and has a stroke of 140 mm. The brake load is 6 kg at 600 mm radius and the mechanical efficiency is 80%. Calculate brake power and mean effective pressure. (VTU, Jul 2004)

[Ans.: 0.377 kW, 0.3888 bar]

25. A single cylinder, two stroke IC engine has a piston of diameter 105 mm and stroke 120 mm. The mean effective pressure is 6 bar. If the crank speed is 1500 rpm, calculate the indicated power of the engine. (VTU, July 2005)

[Ans.: 15.586 kW]

26. A gas engine working on a four stroke cycle has a cylinder of 250 mm diameter, length of stroke 450 mm and is running at 180 rpm. Its mechanical efficiency is 80% when the mean effective pressure is 0.65 MPa. Find: (i) Indicated power, (ii) Brake power and (iii) Friction power. (VTU, Jan 2016)

[Ans.: 21.537 kW, 17.23 kW, 4.307 kW]

27. A four stroke diesel engine has a piston diameter 250 mm and stroke 400 mm. The mean effective pressure is 4 bar and the speed is 500 rpm. The diameter of the brake drum is 1 m and the effective brake load is 400 N. Find the indicated power, brake power and friction power. (VTU, June 2010)

[Ans.: 32.725 kW, 10.472 kW, 22.253 kW]

28. The following data are collected from a four-stroke single cylinder oil engine at full load. Bore = 200 mm, stroke = 280 mm, speed = 300 rpm, indicted mean effective pressure = 5.6 bar, torque on the brake drum = 250 Nm, oil consumed = 4.2 kg/h, calorific value of oil = 41000 kJ/kg. Determine the mechanical efficiency, indicated efficiency and brake thermal efficiency. (VTU, Jan 2010)

[Ans.: 63.77%, 25.75%, 16.42%]