MECHANICAL ENGINEERING
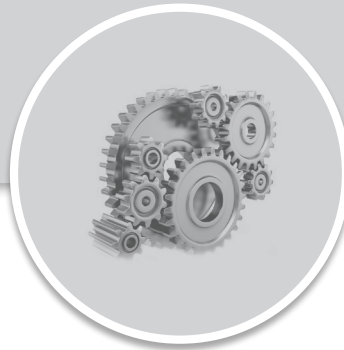
Internal Combustion Engine

Comprehensive Theory
with Solved Examples *and* Practice Questions

MADE EASY
Publications

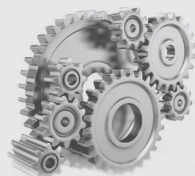# Internal Combustion Engine

CONTENTS
Internal Combustion Engine

CHAPTER 6

CHAPTER 7

CHAPTER 8

■■■■

Basics and Air Standard Cycles

1.1 INTRODUCTION

Engine is a machine used for converting one form of energy into another form. Engine generally converts thermal energy into mechanical work and therefore they are called heat engines. When fuel burns in presence of air, a tremendous amount of heat energy is released. This energy is converted into useful work by means of heat engine. Heat engines are broadly classified into:

(a) **External Combustion Engine:** In external combustion engines, the combustion of fuel takes place outside the engine. For example in steam engine, heat generated due to combustion of fuel is used to generate high pressure steam which is used as working fluid in steam engine. A steam turbine is a good example of external combustion engine.

(b) **Internal Combustion Engine :** In internal combustion engine, combustion take place inside the engine. In this engine chemical energy of fuel is first converted to thermal energy by means of combustion of fuel with air inside the engine. This thermal energy raises the temperature and pressure of the gases inside the engine, and the high pressure gas then expands against the mechanical mechanism of the engine. This expansion of gas is converted by the mechanical linkage of the engine to a rotating crankshaft, which is the output of the engine.

1.2 CLASSIFICATION OF IC ENGINES

The internal combustion engines are usually of reciprocating type. The reciprocating internal combustion engines are classified on the basis of the thermodynamic cycle, mechanical method of operation, type of fuel used, type of ignition, type of cooling system and cylinder arrangement, etc. The detailed classification is given below :

1. **According to number of strokes in the working cycle :**
   (a) **Four Stroke Engine :** In this engine, the thermodynamic cycle is completed in four strokes of piston.
   (b) **Two Stroke Engine :** In this engine, thermodynamic cycle is completed in two strokes of piston.

2. **According to fuel used :**
   (a) **Petrol Engine :** It uses petrol and needs a spark plug to ignite petrol.
   (b) **Diesel Engine :** It uses diesel and self ignition occurs in the combustion chamber due to high temperature of air.

(c) **Gas Engine :** These engine use fuel like CNG, LPG, biogas. Gaseous fuels are better compared to liquid fuels because of reduced ignition delay.

(d) **Multi fuel Engine :** In these engines a gaseous fuel is supplied along with air during initial part of compression and other fuel is injected into combustion space at end of compression stroke.

3. **According to method of ignition :**

(a) **Spark Ignition Engines :** These engines requires an external source of energy for initiation of spark and thereby the combustion process starts.

(b) **Compression Ignition Engines :** In these engines there is no need for an external means to produce ignition. They have high compression ratio which results in high temperature at end of compression process which is sufficient to self ignite the fuel.

4. **According to charge feeding system :**

(a) **Naturally Aspirated Engines :** In these engines admission of air or air-fuel mixture is at atmospheric pressure.

(b) **Supercharged Engines :** In these engines admission of air or air-fuel mixture is at pressure that is above atmospheric pressure.

5. **According to cooling system :**

(a) **Air Cooled Engine :** These engines uses fins to dissipate heat to surrounding to keep the engine within operating temperature.

(b) **Water Cooled Engines :** In these engines water is circulated continuously by means of a external pump which absorbs the engine heat and rejects it to surrounding by using radiator.

6. **According to cylinder arrangements :** To classify engines according to cylinder arrangement two terms must be defined.

(i) **Cylinder Row :** In this arrangement centreline of crankshaft journal is perpendicular to plane containing centreline of engine cylinder.

(ii) **Cylinder Bank :** In this arrangement the centreline of crankshaft journal is parallel to plane containing centreline of engine cylinder.

    (a) **In-Line Engine :** In these engines all cylinders are arranged linearly and transmit power to single crankshaft.

    (b) **V-Engine :** In these engines there are two banks of cylinders inclined at an angle to each other with one crankshaft.

    (c) **Opposed Cylinder Engine :** These engines has two cylinder banks located in same plane on opposite side of crankshaft.

    (d) **Radial Engine :** These engines has more than two cylinders in each row and are equally spaced around crankshaft.
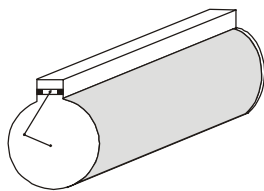

Figure: Inline cylinder Engine   **Figure:** V engine   **Figure:** Opposed cylinder engine   **Figure:** Radial engine
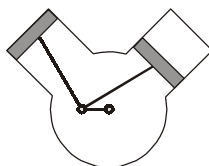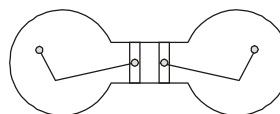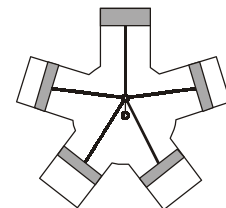
1.3 COMPONENTS OF ENGINES

An internal combustion engine consists of a large number of parts and each part has its own function. A few of them are shown in figure and listed below.

1. **Cylinder :** It is the heart of the engine. The piston reciprocates in the cylinder. It has to withstand high pressure and temperature, and thus it is made strong. Generally, it is made from cast iron. It is provided with a cylinder liner on the inner side and a cooling arrangement on its outer side. For two-stroke engines, it houses exhaust and transfer port.

2. **Cylinder Head :** The top cover of the cylinder, towards TDC, is called cylinder head. It houses the spark plug in petrol engines and fuel injector in Diesel engines. For four stroke cycle engines, the cylinder head is the housing of inlet and exhaust valves.

3. **Piston :** It is the reciprocating member of the engine. It reciprocates in the cylinder. Its top surface is called piston crown and bottom surface is called piston skirt. Its top surface is made flat for four-stroke engines and deflected for two-stroke engines.

Figure : Components of an internal combustion engine

4. **Piston Rings :** Two or three piston rings are provided on the piston. The piston rings seal the space between the cylinder liner and piston in order to prevent leakage (blow by losses) of high-pressure gases, from cylinder to crank case.

5. **Crank :** It is a rotating member. It makes circular motion in the crank case (its housing). Its one end is connected with a shaft called crank-shaft and the other end is connected with a connecting rod.

6. **Crank Case :** It is the housing of the crank and body of the engine to which cylinder and other engine parts are fastened. It also acts as a ground for lubricating oil.

7. **Connecting Rod :** It is a link between the piston and crank. Its one end is connected with a crank while other end with a piston. It transmits power developed on the piston to a crank shaft through crank. It is usually made of medium carbon steel.

8. **Crank Shaft :** It is the shaft, a rotating member, which connects the crank. The power developed by the engine is transmitted outside through this shaft. It is made of medium carbon or alloy steels.

9. **Cooling Fins or Cooling Water Jackets :** During combustion, the engine releases a large amount of heat. Thus the engine parts may be subjected to a temperature at which engine parts may not sustain their properties such as hardness, etc. In order to keep the engine parts within safe temperature limits, the cylinder and the cylinder head are provided with a cooling arrangement. The cooling fins are provided on light duty engines, while a cooling water jacket is provided on medium and heavy duty engines.

10. **Cam Shaft :** It is provided on four-stroke engines. It carries two cams, for controlling the opening and closing of inlet and exhaust valves.

11. **Inlet Valve :** This valve controls the admission of charge into the engine during a suction stroke.

12. **Exhaust Valve :** The removal of exhausted gases after doing work on the piston is controlled by exhaust valve.
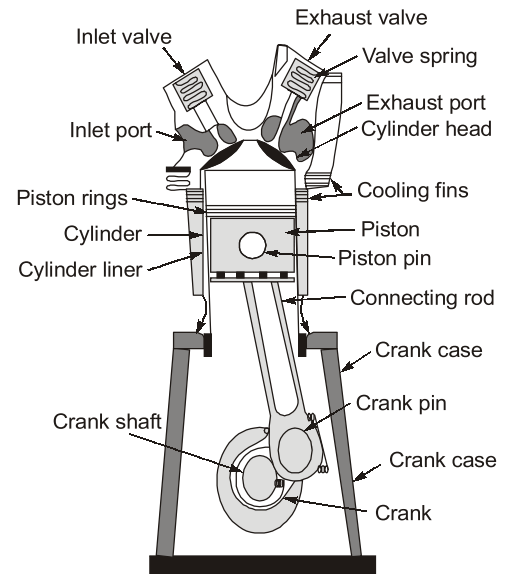
13. **Inlet Manifold :** It is the passage which connects intake system to inlet valve.

14. **Exhaust Manifold :** It is the passage which carries the exhaust gases from the exhaust valve to the atmosphere.

15. (a) **Spark Plug :** It is provided on petrol engines. It produces a high-intensity spark which initiates the combustion process of the charge.

    (b) **Fuel Injector :** It is provided on diesel engines. The diesel fuel is injected in the cylinder at the end of the compression through a fuel injector under very high pressure.

16. (a) **Carburettor :** It is provided with a petrol engine for preparation of a homogeneous mixture of air and fuel (petrol). This mixture, as a charge, is supplied to engine cylinder through suction valve or port.

    (b) **Fuel Pump :** It is provided with a diesel engine. The diesel is taken from the fuel tank, its pressure is raised in the fuel pump and then it is delivered to fuel injector.

17. **Flywheel :** It is mounted on the crank shaft and is made of cast iron. It stores energy in the form of inertia, when energy is in excess and it gives back energy when it is in deficit. In other words, it minimizes the speed fluctuations on the engine.

| **EXAMPLE : 1.1** | The gudgeon pin of an IC engine is made hollow |

(a) To save material in order to decrease cost.
(b) To have more section modulus for same volume.
(c) To have more polar modulus for same volume.
(d) To reduce weight for having low inertia effect.

Solution: (d)

Less the inertia effects, more the net force on piston.

1.4   BASIC TERMINOLOGY

The basic terminology used for volumes and measurements in the cylinder region is presented and shown in figure.
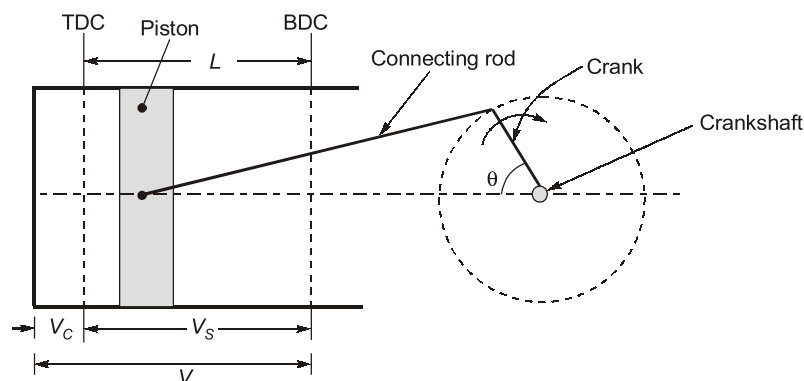
Figure : Basic Terminology

1. **Bore (d) :** It is the inside diameter of the engine cylinder. It is called the bore as it is made through a boring process.

2. **Stroke (L) :** During the travel of the piston, there is an upper as well as a lower limiting position at which the direction of motion of the piston is reversed. The linear distance through which the piston travels between the extreme upper and lower positions of the piston is called the stroke. It is equal to two times the crank radius, $L = 2r$, where r is the crank radius.

3. **Top Dead Centre (TDC) :** When the piston is at the topmost position of the cylinder during its travel, that position is called the Top Dead Centre. At this position the piston velocity is zero and the piston reverses its direction of motion to travel downwards. It is the dead centre when the piston is farthest from the crankshaft.

4. **Bottom Dead Centre (BDC) :** When the piston is at the bottom-most position of the cylinder during its travel, that position is called the Bottom Dead Centre. At this position the piston velocity is zero and the piston reverses its direction of motion to travel upwards. It is the dead centre when the piston is nearest to the crankshaft.

5. **Clearance Volume (V_c) :** When the piston is at the TDC position, the volume contained in the cylinder above the top of the piston is called the clearance volume. The piston cannot occupy any part of this volume and always keeps this volume clear.

6. **Piston Displacement or Swept Volume (V_s) :** It is the volume swept through by the piston in moving between the TDC and the BDC, i.e.,

$$V_s = \frac{\pi}{4} d^2 L \qquad \qquad \ldots \text{(i)}$$

7. **Cylinder Volume (V) :** The cylinder volume includes both the clearance volume and the swept volume, i.e.,

$$V = V_c + V_s \qquad \qquad \ldots \text{(ii)}$$

8. **Compression Ratio (r) :** It is the ratio of the volume when the piston is at BDC to the volume when the piston is at TDC. Hence, it is the ratio of total cylinder volume to clearance volume.

$$r = \frac{V}{V_c} = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c} \qquad \qquad \ldots \text{(iii)}$$

9. **Mean Piston Speed :** As the piston moves inside the engine cylinder its speed changes continuously. It is zero at TDC and BDC and maximum nearly at the mid-position of TDC and BDC. The crank angle θ is zero at TDC, it is almost 90° when the piston speed is maximum and 180° at BDC. In the limit of infinitely long connecting rod, the motion is simple harmonic and maximum speed will be at 90° crank angle. Thus in a half rotation of the crank, the piston moves a distance equal to the length of the stroke, L. In full rotation, the distance travelled by piston will be $2L$. If N is the engine speed in revolutions per minute (rpm) and L is in metres, the mean piston speed will be $2LN/60$ m/s.

$$\text{Mean or Average piston speed, } \overline{u}_p = \frac{2LN}{60} \qquad \qquad \ldots \text{(iv)}$$

1.5 PETROL ENGINE

The ordinary Otto-cycle engine is a four stroke engine; that is, its piston makes four strokes, two toward the cylinder head and two away from the cylinder head (TDC). By suitable design, it is possible to operate an Otto-cycle as a two-stroke cycle engine with one power stroke in every revolution of the engine. Thus, the power of a two-stroke cycle engine is theoretically double that of a four-stroke cycle engine of comparable size. These engines are also called spark ignition engines.

1.5.1 Two-Stroke Petrol Engine

All essential operations are carried out in one rotation of the crank shaft or two-strokes of the piston. Therefore, the engine is called a two-stroke or two-stroke cycle engine.
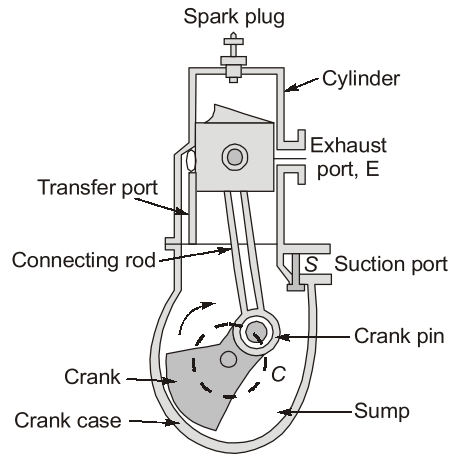
Figure : Two-stroke petrol engine

(a) **Construction Details :** A two-stroke petrol engine is shown in figure. It consists of a cylinder, cylinder head, piston, piston rings, connecting rod, crank, crank case, crank shaft, etc. The charge (air-fuel mixture) is prepared outside the cylinder in the carburetor. In the simplest type of two-stroke engine, the ports are provided for charge inlet and exhaust outlet, which are uncovered and closed by the moving piston. The suction port with a reed-type valve is used for induction of charge into the crank case, the transfer port is used for transfer of charge from the crank case to the cylinder and the exhaust port serves the purpose of discharging the burnt gases from the cylinder. The spark plug is located in the cylinder head.

(a) Charge transfer and scavenging **(b) Start of compression** **(c) Compression and Suction** **(d) Power and Exhaust**
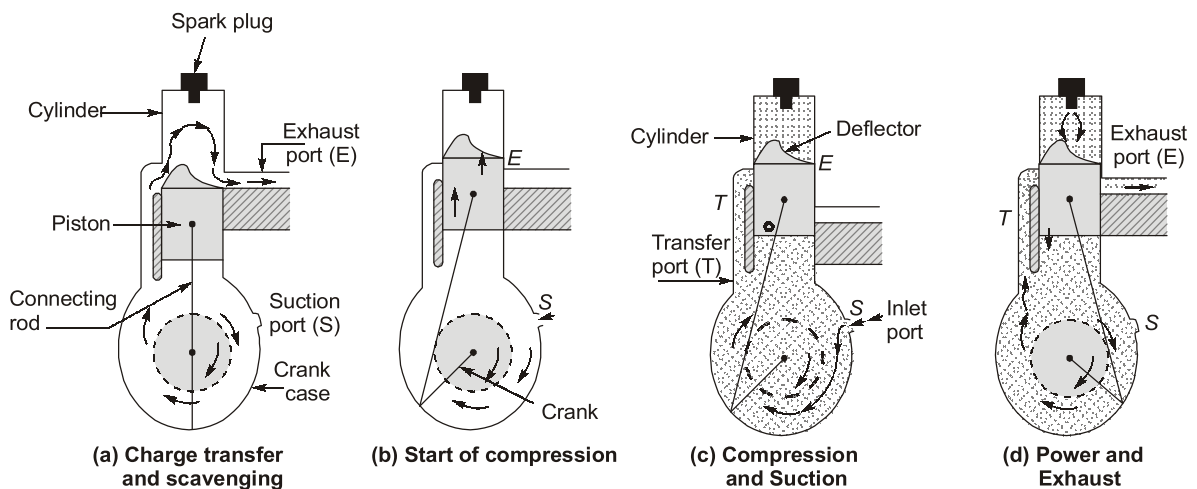
Figure : Operations of a two-stroke petrol engine

(b) **Operation :** In a two-stroke engine, the inlet, transfer and exhaust ports are covered and uncovered by a moving piston. The following operations take place in a two-stroke or in one cycle of the engine.

    (i) **Charge transfer and Scavenging :** When the piston is near to the crank case (bottom dead centre), the transfer port and exhaust port are uncovered by the piston. A mixture of air and fuel

as a charge, slightly compressed in the crank case, enters through the transfer port *T* and drives out the burnt gases of the previous cycle through the exhaust port *E*.

In a two-stroke engine, the piston top is made deflected. Therefore, the incoming charge is directed upward, and aids in sweeping of the burnt gases out of the cylinder. This operation is known as scavenging (a gas-exchange process). As the piston moves upward, the fresh charge passes into the cylinder for 1/6 th of the revolution and the exhaust port remains open a little longer than the transfer port.

(ii) Compression and Suction : As the piston moves upward, both the transfer port and exhaust port are covered by the piston and the charge trapped in the cylinder is compressed by the piston's upward movement. At the same time, a partial vacuum is created into the crank case, the suction port *S* opens by moving the crank and the fresh charge enters the crank case.

(iii) Combustion : When the piston reaches at its end of stroke nearer to the cylinder head or at the top dead centre, a high-intensity spark from the spark plug ignites the charge and initiates the combustion in the cylinder.

(iv) Power and Exhaust : The burning gases apply pressure on the top of the piston, and the piston is forced downward as a result of pressure generated.

As the piston descends through about 80% of the expansion stroke, the exhaust port *E* is uncovered by the piston, and the combustion gases leave the cylinder by pressure difference and at the same time, the underside of the piston causes compression of charge taken into crank case.

(v) Charging : The slightly compressed charge in the crank case passes through the transfer port and enters the cylinder as soon as it is uncovered by the descending piston and when it approaches the bottom dead centre, the cycle is completed.

Figure : *p-V* diagram and schematic of a two-stroke petrol engine

The *p-V* diagram and port-timing diagram for a two-stroke petrol engine are shown in figure.

IPU = Inlet port uncovered 40° before TDC
IPC = Inlet port closed 40° after TDC
EPU = Exhaust port uncovered 60° before BDC
EPC = Exhaust port closed 60° after BDC
TPU = Transfer port uncovered 50° before BDC
TPC = Transfer port closed 50° after BDC
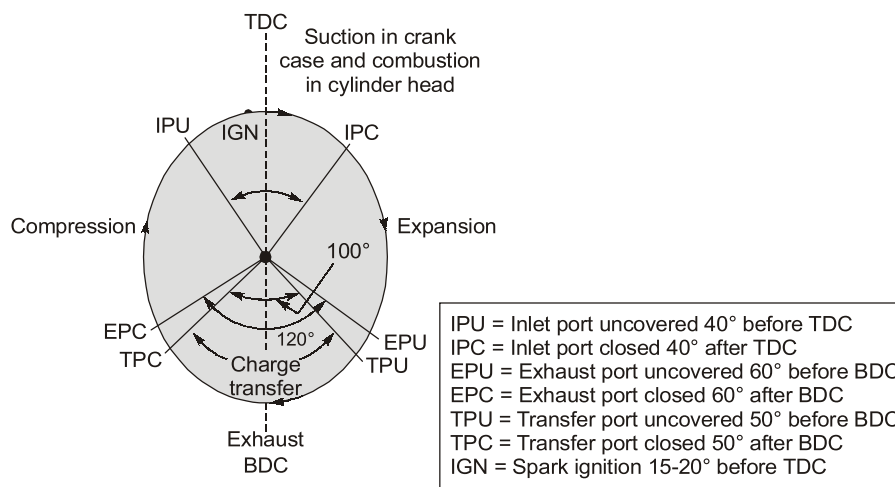IGN = Spark ignition 15-20° before TDC

Figure : Port time diagram

(c) Applications : Two-stroke gasoline engines are used where simplicity and low cost are main considerations. These engines have a little higher specific fuel consumption.

1. 50 cc – 70 cc engines are used in mopeds, lawn movers and non-gear vehicles.
2. 100 – 150 cc engines are commonly used in scooters and motor cycles.
3. 250 cc two-stroke engines are used in high-powered (racing) motor cycles.
4. These engines can also be used in small electric generator sets, pumping sets and motor boats.

1.5.2 Four-Stroke Cycle Petrol Engine

All operations are carried out in four strokes of the piston, i.e., two revolutions of the crank shaft. Therefore, the engine is called a four stroke engine.

(a) Constructional Details : Similar to a two-stroke engine, it also consists of a cylinder, cylinder head attached with spark plug, piston attached with piston ring, connecting rod, crank, crank shaft, etc. In a four-stroke engine, valves are used instead of ports. There are suction and exhaust valves. These valves are operated by cams attached on a separate shaft, called a cam shaft. It is rotated at half the speed of a crank shaft.

(b) Operation : The travel of the piston from one dead centre to another is called piston stroke and a four stroke cycle consists of four strokes as suction, compression, expansion and exhaust strokes.

(i) Suction Stroke : The suction valve opens, exhaust valve remains closed as shown in figure. The piston moves from the top dead centre to the bottom dead centre, the charge (mixture of fuel and air prepared in the carburettor) is drawn into the cylinder.

(ii) Compression Stroke : When the piston moves from the bottom dead centre to top dead centre, and the suction valve is closed, exhaust valve remains closed as shown in figure. The trapped charge in the cylinder is compressed by the upward moving piston. As the piston approaches the top dead centre, the compression stroke completes.

(iii) Expansion Stroke : At the end of the compression stroke, the compressed charge is ignited by a high-intensity spark created by a spark plug, combustion starts and the high-pressure burning gases force the piston downward as shown in figure. The gas pressure performs work, therefore, it is also called working stroke or power stroke. When the piston approaches the bottom dead centre in its downward stroke then this stroke is completed. In this stroke, both valves remains closed.

(iv) Exhaust Stroke : When the piston moves from the bottom dead centre to the top dead centre, only the exhaust valve opens and burnt gases are expelled to surroundings by upward movement of the piston as shown in figure. This stroke is completed when the piston approaches the top dead centre. Thus, one cycle of a four stroke petrol engine is completed. The next cycle begins with piston movement from the top dead centre to the bottom dead centre.

(c) Valve Timing : Theoretically, in a four-stroke cycle engine, the inlet and exhaust valves open and close at dead centres as shown in figure.

A typical valve-timing diagram for a four-stroke petrol engine is shown in figure. The angular positions in terms of crank angle with respect to TDC and BDC position of piston are quoted on the diagram.

When the inlet valve and exhaust valve remain open simultaneously, it is called a valve overlap.

(d) Applications : These engines are mostly used on automobiles, motor cycles, cars, buses, trucks, aeroplanes, small pumping sets, mobile electric generators, etc.

Nowadays, the four-stroke petrol engines have been replaced by four-stroke Diesel engines for most applications.

(a) Suction stroke **(b) Compression stroke** **(c) Power stroke** **(d) Exhaust stroke**
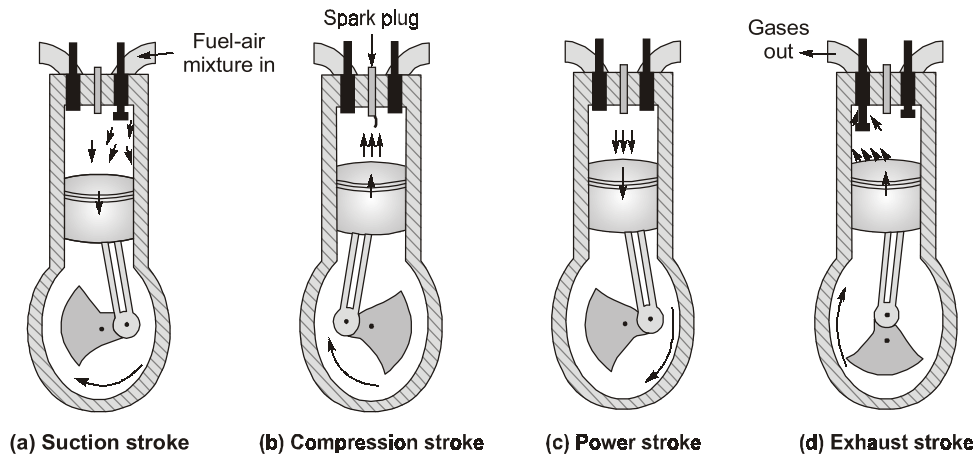
Figure : Operation of four stroke petrol engine
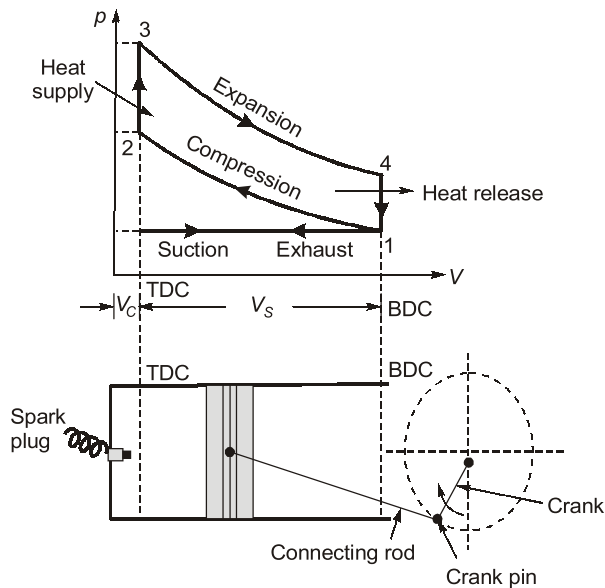

Figure : Theoretical p-V diagram for a four-stroke petrol engine
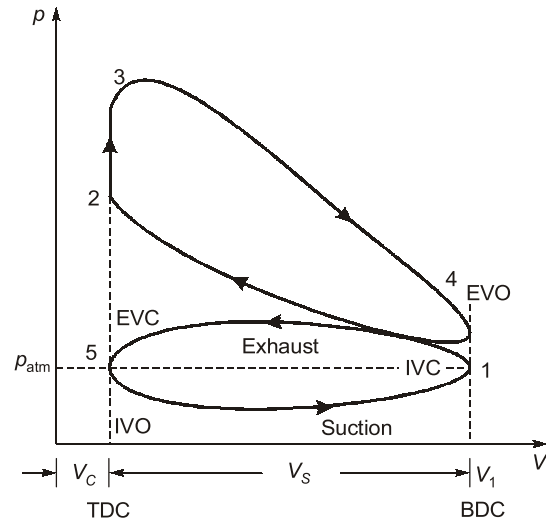

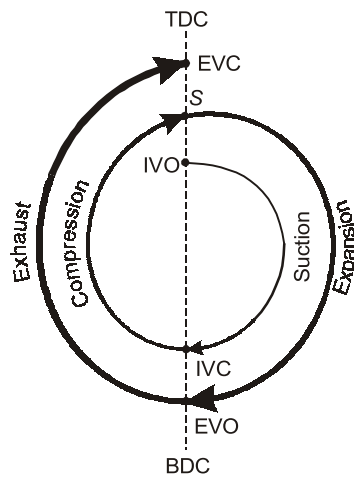**Figure :** Actual p-V diagram for four-stroke petrol engine

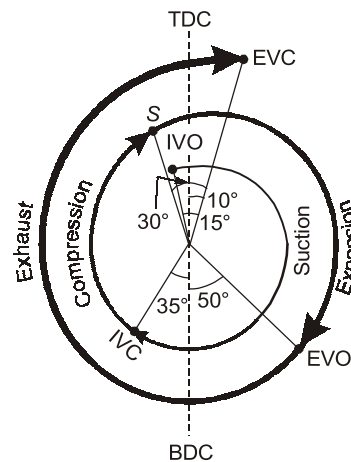**Figure:** Theoretical valve timing diagram of a four-stroke cycle

Figure: The actual valve timing diagram for a four-stroke petrol engine

IVO	= Inlet valve opens when piston at TDC	IVO	= Inlet valve opens about 15° before TDC
IVC	= Inlet valve closes, when piston reaches BDC	IVC	= Inlet valve closes 20° – 40° after BDC to take advantage of rapidly moving gas
S	= Spark produces, when piston reaches TDC	S	= Spark occurs 20° – 40° before TDC
EVO	= Exhaust valve opens when piston at BDC	EVO	= Exhaust valve opens about 50° before BDC
EVC	= Exhaust valve closes, when piston at TDC	EVC	= Exhaust valve close about 0° to 10° after TDC

EXAMPLE : 1.2

Statement (I): Two stroke engines have high fuel consumption and lower thermal efficiency as compared to four stroke engines.

Statement (II): During scavenging, some of the fresh charge containing fuel escapes with the exhaust.

(a) Both Statement (I) and Statement (II) are true and Statement (II) is the correct explanation of Statement (I).

(b) Both Statement (I) and Statement (II) are true but Statement (II) is not a correct explanation of Statement (I).

(c) Statement (I) is true but Statement (II) is false.

(d) Statement (I) is false but Statement (II) is true.

Solution: (a)

1.6   DIESEL ENGINE

All engines using diesel as a fuel operate on the Diesel cycle. They work similar to a petrol engine except they take in only air as charge during suction, and fuel is injected at the end of the compression stroke. The Diesel engines have a fuel injector instead of a spark plug in the cylinder head. The diesel engines use a high compression ratio in the range of 14 to 21. The temperature of intake air reaches quite a high value at the end of compression. Therefore, the injected fuel is self ignited. The Diesel engines use a heterogeneous air-fuel mixture, ratio ranging from 20 to 60.

Figure : Schematic of two-stroke Diesel engine

1.6.1   Two-stroke Diesel Engine

The operation of a two-stroke Diesel engine is similar to a petrol engine, except it takes air as charge and fuel is injected at the end of the compression stroke. It uses a high compression ratio. Therefore, the injected fuel is self-ignited.

Operation : Both inlet and exhaust take place through the cylinder ports which are covered and uncovered by the piston.

(i) **Charge Transfer and Scavenging :** When the piston is nearer to the crank case (bottom dead centre), the transfer port and exhaust port are uncovered by the piston and the slightly compressed air enters into the cylinder through the transfer port and helps to scavenge the remaining burnt gases from the cylinder. The charge transfer and scavenging continue till the piston completes its downward stroke and further, it moves upward and covers the transfer port.
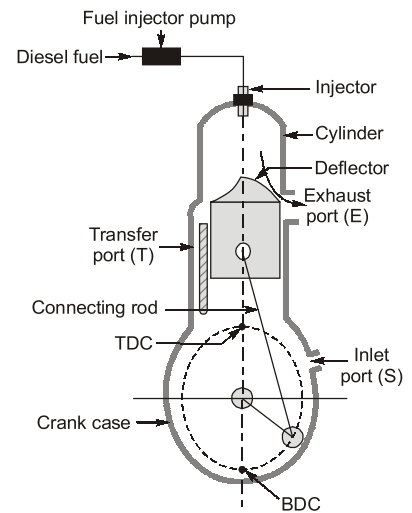
IMPORTANT POINTS TO REMEMBER

- The Internal Combustion (I.C.) engine is a heat engine that converts the chemical energy of a fuel into mechanical energy, usually mechanical energy available on a rotating output shaft. Chemical energy of the fuel is first converted to thermal energy by means of combustion of fuel with air inside the engine.
- Spark plug is provided on petrol engines. It produces a high-intensity spark which initiates the combustion process of the charge.
- Fuel injector is provided on Diesel engines. The Diesel fuel is injected in the cylinder at the end of the compression through a fuel injector under very high pressure.
- Carburettor is provided with a petrol engine for preparation of a homogeneous mixture of air and fuel (petrol). This mixture, as a charge, is supplied to engine cylinder through suction valve or port.
- Fuel pump is provided with a Diesel engine. The diesel is taken from the fuel tank, its pressure is raised in the fuel pump and then it is delivered to fuel injector.
- Flywheel is mounted on the crank shaft and is made of cast iron. It stores energy in the form of inertia, when energy is in excess and it gives back energy when it is in deficit. In other words, it minimizes the speed fluctuations on the engine.
- When the piston is at the TDC position, the volume contained in the cylinder above the top of the piston is called the clearance volume.
- It is the volume swept through by the piston in moving between the TDC and the BDC.
- It is the ratio of the volume when the piston is at BDC to the volume when the piston is at TDC. Hence, it is the ratio of total cylinder volume to clearance volume.
- All essential operations are carried out in one revolution of the crank shaft or two strokes of the piston. Therefore, the engine is called a two-stroke or two-stroke cycle engine.
- All operations are carried out in four strokes of the piston, i.e., two revolutions of the crank shaft. Therefore, the engine is called a four stroke engine.

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OBJECTIVE BRAIN TEASERS

Q.1 With increasing temperature of intake air, IC engine efficiency
(a) decreases
(b) increases
(c) remains same
(d) depends on other factors

Q.2 The silencer of an internal combustion engine
(a) reduces noise
(b) decreases brake specific fuel consumption (*bsfc*)
(c) increases *bsfc*
(d) has no effect on its efficiency

Q.3 A Diesel engine is usually more efficient than a spark ignition engine because
(a) diesel being a heavier hydrocarbon, releases more heat per kg than gasoline
(b) the air standard efficiency of diesel cycle is higher than the Otto cycle, at a fixed compression ratio
(c) the compression ratio of a diesel engine is higher than that of an SI engine
(d) self-ignition temperature of diesel is higher than that of gasoline

Q.4 Piston compression rings are made of
(a) Cast iron   (b) Bronze
(c) Aluminum   (d) White metal

Q.5 **Statement (I):** For a given compression ratio, the thermal efficiency of the Diesel cycle will be higher than that of the Otto cycle.
Statement (II): In the Diesel cycle, work is also delivered during heat addition.
(a) Both Statement (I) and Statement (II) are true and Statement (II) is the correct explanation of Statement (I).
(b) Both Statement (I) and Statement (II) are true but Statement (II) is not a correct explanation of Statement (I).
(c) Statement (I) is true but Statement (II) is false.
(d) Statement (I) is false but Statement (II) is true.

Q.6 Which one of the following p-T diagrams illustrates the Otto cycle of an ideal gas?

(a)

(b)

(c)

(d)
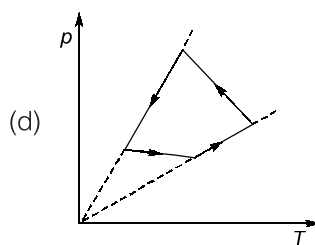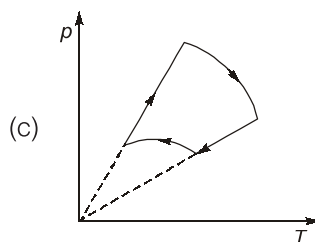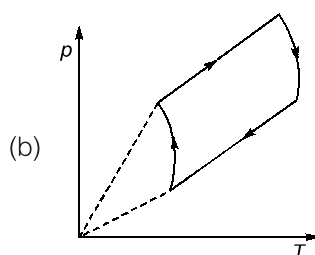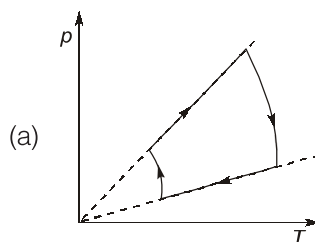
ANSWER KEY

1. (a)	**2.** (a)	**3.** (c)	**4.** (a)	**5.** (d)
6. (a)				

CONVENTIONAL BRAIN TEASERS

Q.1 In an engine working on Dual cycle, the temperature and pressure at the beginning of the cycle are 90°C and 1 bar respectively. The compression ratio is 9. The maximum pressure is limited to 68 bar and total heat supplied per kg of air is 1750 kJ.

Determine:
(i) Pressure and temperature at all salient points
(ii) Air standard efficiency
(iii) Mean effective pressure.

Solution:

Initial pressure, p_1 = 1 bar
Initial temperature, T_1 = 90° = 363 K
Compression ratio, r = 9
Maximum pressure, p_3 = p_4 = 68 bar
Total heat supplied = 1750 kJ kg

(i) Pressures and temperatures at salient points:

For the isentropic process 1-2,

$$p_1 V_1^\gamma = p_2 V_2^\gamma$$

$$p_2 = p_1 \times \left(\frac{V_1}{V_2}\right)^\gamma = 1 \times (r)^\gamma = 1 \times (9)^{1.4}$$

$$= \textbf{21.67 bar}$$

Also, $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r)^{\gamma-1} = (9)^{1.4-1} = 2.408$$

∴ $$T_2 = T_1 \times 2.408 = 363 \times 2.408 = \textbf{874.1 K}$$
$$p_3 = p_4 = 68 \text{ bar}$$

For the constant volume process 2–3,

$$\frac{p_2}{T_2} = \frac{p_3}{T_3}$$

∴ $$T_3 = T_2 \times \frac{p_3}{p_2} = 874.1 \times \frac{68}{21.67} = \textbf{2742.9 K}$$

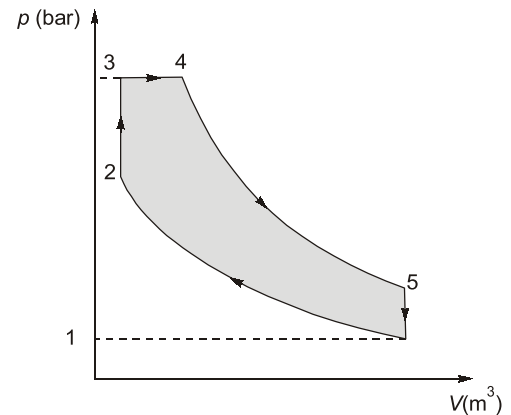Heat added at constant volume = $c_v(T_3 - T_2) = 0.71(2742.9 - 874.1)$
= 1326.8 kJ/kg

∴ Heat added at constant pressure = Total heat added – Heat added at constant volume
= 1750 – 1326.8 = 423.2 kJ/kg

∴ $$c_p(T_4 - T_3) = 423.2$$
or $$1.0(T_4 - 2742.9) = 423.2$$
∴ $$T_4 = \textbf{3166 K}$$

For constant pressure process 3–4, $$\rho = \frac{V_4}{V_3} = \frac{T_4}{T_3} = \frac{3166}{2742.9} = 1.15$$

For adiabatic (or isentropic) process 4–5,

$$\frac{V_5}{V_4} = \frac{V_5}{V_2} \times \frac{V_2}{V_4} = \frac{V_1}{V_2} \times \frac{V_3}{V_4} = \frac{r}{\rho} \qquad \left(\because \rho = \frac{V_4}{V_3} \right)$$

Also

$$p_4 V_4^\gamma = p_5 V_5^\gamma$$

$$\therefore \qquad p_5 = p_4 \times \left(\frac{V_4}{V_5} \right)^\gamma$$

$$= 68 \times \left(\frac{\rho}{r} \right)^\gamma = 68 \times \left(\frac{1.15}{9} \right)^{1.4} = \textbf{3.81 bar}$$

Again,

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_5} \right)^{\gamma-1} = \left(\frac{\rho}{r} \right)^{\gamma-1} = \left(\frac{1.15}{9} \right)^{1.4-1} = 0.439$$

$$\therefore \qquad T_5 = T_4 \times 0.439 = 3166 \times 0.439 = \textbf{1389.9 K}$$

(ii) Air standard efficiency :
Heat rejected during constant volume process 5–1,

$$Q_R = c_v (T_5 - T_1) = 0.71(1389.8 - 363) = 729 \text{ kJ/kg}$$

$$\therefore \qquad \eta_{air-standard} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_s - Q_R}{Q_s}$$

$$= \frac{1750 - 729}{1750} = \textbf{0.5834} = \textbf{58.34\%}$$

(iii) Mean effective pressure, p_m :

$$p_m = \frac{\text{Work done per cycle}}{\text{Stroke volume}}$$

or

$$p_m = \frac{1}{V_s} \left[p_3 (V_4 - V_3) + \frac{p_4 V_4 - p_4 V_5}{\gamma - 1} - \frac{p_2 V_2 - p_1 V_1}{\gamma - 1} \right]$$

$$V_1 = V_5 = rV_c, \ V_2 = V_3 = V_c, \ V_4 = \rho V_c,$$
$$V_s = (r-1)V_c$$

$$\therefore \qquad r = \frac{V_s + V_c}{V_c} = 1 + \frac{V_s}{V_c}$$

$$\therefore \qquad V_s = (r-1)V_c$$

$$\therefore \qquad p_m = \frac{1}{(r-1)V_c} \left[p_3 (\rho V_c - V_c) + \frac{p_4 \rho V_c - p_5 \times rV_c}{\gamma - 1} - \frac{p_2 V_c - p_1 rV_c}{\gamma - 1} \right]$$

$$r = 9, \ \rho = 1.15, \ \gamma = 1.4$$
$$p_1 = 1 \text{ bar}, \ p_2 = 21.67 \text{ bar},$$
$$p_3 = p_4 = 68 \text{ bar}, \ p_5 = 3.81 \text{ bar}$$

Substituting the above values in the above equation, we get

$$p_m = \frac{1}{(9-1)} \left[68(1.15 - 1) + \frac{68 \times 1.15 - 3.81 \times 9}{1.4 - 1} - \frac{21.67 - 9}{1.4 - 1} \right]$$

$$= \frac{1}{8} (10.2 + 109.77 - 31.67) = \textbf{11.04 bar}$$

Q.2 An engine with 200 mm cylinder diameter and 300 mm stroke works on theoretical Diesel cycle. The initial pressure and temperature of air used are 1 bar and 27°C. The cut-off is 8% of the stroke. Determine:

(i)   Pressure and temperatures at all salient points.

(ii) Theoretical air standard efficiency.

(iii) Mean effective pressure.

(iv) Power of the engine if the working cycles per minute are 380.

Assume that compression ratio is 15 and working fluid is air.

Consider all conditions to be ideal.

Solution:

Cylinder diameter,	D	= 200 mm or 0.2 m,
Stroke length,	L	= 300 mm or 0.3 m,
Initial pressure,	p_1	= 1.0 bar,
Initial temperature,	T_1	= 27°C = 27 + 273
		= 300 K

$$\text{Cut-off} = \frac{8}{100}V_s = 0.08\,V_s$$
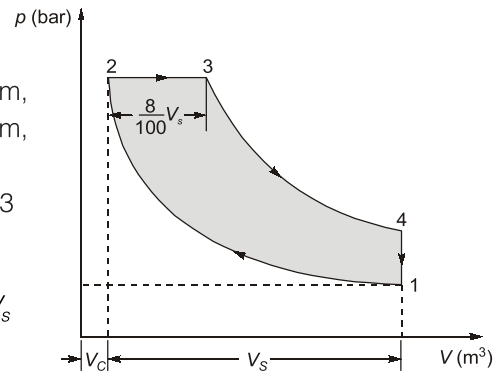
(i)   Pressures and temperatures at salient points :

Now, stroke volume,

$$V_s = \frac{\pi}{4}D^2L = \frac{\pi}{4}\times 0.2^2 \times 0.3 = 0.00942 \text{ m}^3$$

$$V_1 = V_s + V_c = V_s + \frac{V_s}{r-1} \qquad \left[\because V_c = \frac{V_s}{r-1}\right]$$

$$= V_s\left(1+\frac{1}{r-1}\right) = \frac{r}{r-1}\times V_s$$

i.e.

$$V_1 = \frac{15}{15-1}\times V_s = \frac{15}{14}\times 0.00942 = 0.0101 \text{ m}^3$$

Mass of the air the cylinder can be calculated by using the gas equation,

$$p_1 V_1 = mRT_1$$

$$m = \frac{p_1 V_1}{RT_1} = \frac{1\times 10^5 \times 0.0101}{287 \times 300} = 0.0117 \text{ kg/cycle}$$

For the adiabatic (or isentropic) process 1–2

$$p_1 V_1^\gamma = p_2 V_2^\gamma$$

or

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^\gamma = (r)^\gamma$$

$$\therefore \quad p_2 = p_1.(r)^\gamma = 1 \times (15)^{1.4} = \textbf{44.31 bar}$$

Also,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$= (r)^{\gamma-1} = (15)^{1.4-1} = 2.954$$

$$\therefore \quad T_2 = T_1 \times 2.954 = 300 \times 2.954 = \textbf{886.2 K}$$

$$V_2 = V_c = \frac{V_s}{r-1} = \frac{0.00942}{15-1} = \textbf{0.0006728 m}^3$$

$$p_2 = p_3 = \textbf{44.31 bar}$$

$$\text{\% cut-off ratio} = \frac{\rho - 1}{r - 1}$$

$$\frac{8}{100} = \frac{\rho - 1}{15 - 1}$$

i.e., $\qquad \rho = 0.08 \times 14 + 1 = 12.12$

∴ $\qquad V_3 = \rho V_2 = 2.12 \times 0.0006728 = 0.001426 \text{ m}^3$

V_3 can also be calculated as follows : $\quad V_3 = 0.08 \, V_s + V_c = 0.08 \times 0.00942 + 0.0006728$

$$= 0.001426 \, \text{m}^3$$

For the constant pressure process 2 – 3,

$$\frac{V_3}{T_3} = \frac{V_2}{T_2}$$

∴ $\qquad T_3 = T_2 \times \frac{V_3}{V_2} = 886.2 \times \frac{0.001426}{0.0006728} = \textbf{1878.3 K}$

For the isentropic process 3 – 4, $\qquad p_3 V_3^\gamma = p_4 V_4^\gamma$

$$p_4 = p_3 \times \left(\frac{V_3}{V_4}\right)^\gamma = p_3 \times \frac{1}{(7.07)^{1.4}} = \frac{44.31}{(7.07)^{1.4}}$$

$$= \textbf{2.866 bar}$$

∵ $\qquad \frac{V_4}{V_3} = \frac{V_4}{V_2} \times \frac{V_2}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3} = \frac{r}{\rho}$

∵ $\qquad V_4 = V_1 = \frac{15}{2.12} = 7.07$

Also, $\qquad \frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{1}{7.07}\right)^{1.4-1} = 0.457$

∴ $\qquad T_4 = T_3 \times 0.457 = 1878.3 \times 0.457 = \textbf{858.38 K}$

$$V_4 = V_1 = 0.0101 \, \text{m}^3$$

(ii) Theoretical air standard efficiency :

$$\eta_{\text{diesel}} = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \left[\frac{\rho^\gamma - 1}{\rho - 1} \right] = 1 - \frac{1}{1.4(15)^{1.4-1}} \left[\frac{(2.12)^{1.4} - 1}{2.12 - 1} \right]$$

$$= 1 - 0.2418 \times 1.663 = \textbf{0.598 or 59.8 \%}$$

(iii) Mean effective pressure, p_m;

Mean effective pressure of Diesel cycle is given by

$$p_m = \frac{p_1(r)^\gamma \left[\gamma(\rho - 1) - r^{1-\gamma}(\rho^\gamma - 1) \right]}{(\gamma - 1)(r - 1)}$$

$$= \frac{1 \times (15)^{1.4} \left[1.4(2.12 - 1) - (15)^{1-1.4}(2.12^{1.4} - 1) \right]}{(1.4 - 1)(15 - 1)}$$

$$= \frac{44.31 \left[1.568 - 0.338 \times 1.863 \right]}{0.4 \times 14} = \textbf{7.424 bar}$$