

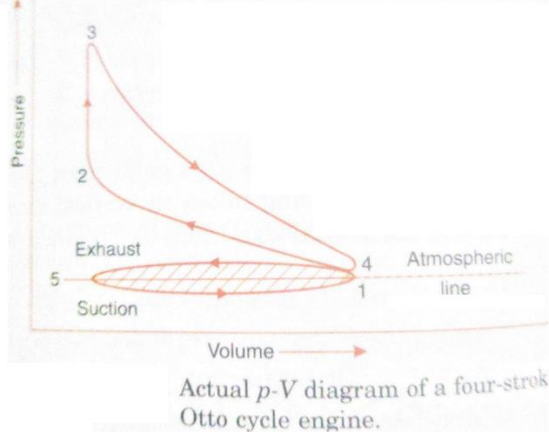
**24AG301- APPLIED THERMODYNAMICS AND THERMAL
SYSTEMS IN AGRICULTURAL ENGINEERING**

**UNIT 2 INTERNAL COMBUSTION ENGINES FOR
AGRICULTURE**

HANDLED BY

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Otto cycle

- The point 1 represents that cylinder is full of air with volume V_1 , pressure p_1 and absolute temperature T_1 .
- Line 1-2 represents the *adiabatic compression* of air due to which p_1 , V_1 and T_1 change to p_2 , V_2 and T_2 respectively.
- Line 2-3 shows the *supply of heat* to the air at *constant volume* so that p_2 and T_2 change to p_3 and T_3 (V_3 being the same as V_2).
- Line 3-4 represents the *adiabatic expansion* of the air. During expansion p_3 , V_3 and T_3 change to a final value of p_4 , V_4 or V_1 and T_4 respectively.
- Line 4-1 shows the *rejection of heat* by air at *constant volume* till original state (point 1) reaches.

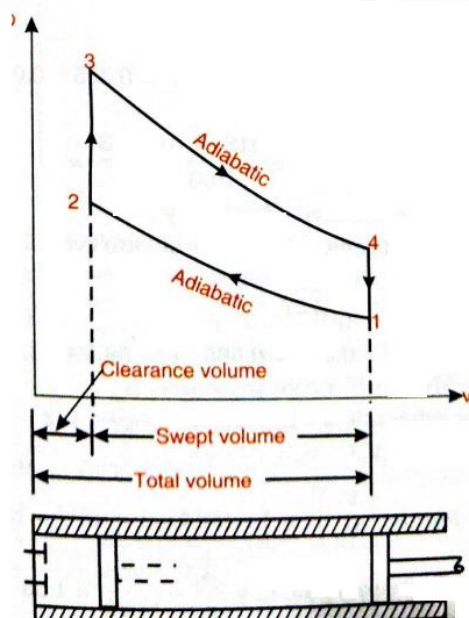
Consider **1 kg of air** (working substance) :

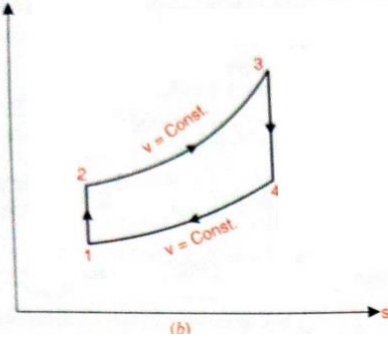
Heat supplied at constant volume = $c_v(T_3 - T_2)$.

Heat rejected at constant volume = $c_v(T_4 - T_1)$.

But, work done = Heat supplied – Heat rejected
 $= c_v(T_3 - T_2) - c_v(T_4 - T_1)$

$$\begin{aligned} \therefore \text{Efficiency} &= \frac{\text{Work done}}{\text{Heat supplied}} \\ &= \frac{c_v(T_3 - T_2) - c_v(T_4 - T_1)}{c_v(T_3 - T_2)} \\ &= 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad \dots(i) \end{aligned}$$





Let compression ratio, $r_c (= r) = \frac{v_1}{v_2}$

expansion ratio, $r_e (= r) = \frac{v_4}{v_3}$

(These two ratios are same in this cycle)

As
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1}$$

Then,
$$T_2 = T_1 \cdot (r)^{\gamma-1}$$

Similarly,
$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3} \right)^{\gamma-1}$$

or
$$T_3 = T_4 \cdot (r)^{\gamma-1}$$

Inserting the values of T_2 and T_3 in equation (i), we get

$$\eta_{\text{otto}} = 1 - \frac{T_4 - T_1}{T_4 \cdot (r)^{\gamma-1} - T_1 \cdot (r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{r^{\gamma-1}(T_4 - T_1)} = 1 - \frac{1}{(r)^{\gamma-1}}$$

This expression is known as the **air standard efficiency of the Otto cycle**.

$$\begin{aligned} \therefore W &= \frac{1}{\gamma-1} \left[p_4 v_4 \left(\frac{p_3 v_3}{p_4 v_4} - 1 \right) - p_1 v_1 \left(\frac{p_2 v_2}{p_1 v_1} - 1 \right) \right] \\ &= \frac{1}{\gamma-1} \left[p_4 v_4 \left(\frac{p_3}{p_4 r} - 1 \right) - p_1 v_1 \left(\frac{p_2}{p_1 r} - 1 \right) \right] \\ &= \frac{v_1}{\gamma-1} \left[p_4 (r^{\gamma-1} - 1) - p_1 (r^{\gamma-1} - 1) \right] \\ &= \frac{v_1}{\gamma-1} \left[(r^{\gamma-1} - 1)(p_4 - p_1) \right] \\ &= \frac{p_1 v_1}{\gamma-1} \left[(r^{\gamma-1} - 1)(r_p - 1) \right] \end{aligned}$$

Mean effective pressure (p_m) is given by :

$$p_m = \left[\left(\frac{p_3 v_3 - p_4 v_4}{\gamma-1} - \frac{p_2 v_2 - p_1 v_1}{\gamma-1} \right) \div (v_1 - v_2) \right] \text{ bar}$$

Also
$$p_m = \frac{\left[\frac{p_1 v_1}{\gamma-1} (r^{\gamma-1} - 1)(r_p - 1) \right]}{(v_1 - v_2)}$$

$$r = \frac{V_s + V_c}{V_c} = \frac{0.0184 + 0.00263}{0.00263} = 8.$$

(i) Air standard efficiency :

The air standard efficiency of Otto cycle is given by

$$\eta_{\text{Otto}} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(8)^{1.4-1}} = 1 - \frac{1}{(8)^{0.4}}$$
$$= 1 - 0.435 = \mathbf{0.565 \text{ or } 56.5\% \text{ (Ans.)}}$$

(ii) Mean effective pressure, p_m :

For adiabatic (or isentropic) process 1-2

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

$$p_2 = p_1 \left(\frac{V_1}{V_2} \right)^\gamma = 1 \times (r)^{1.4} = 1 \times (8)^{1.4} = 18.38 \text{ bar}$$

$$\therefore \text{Pressure ratio, } r_p = \frac{p_3}{p_2} = \frac{25}{18.38} = 1.36$$

The mean effective pressure is given by

$$p_m = \frac{p_1 r [(r^{\gamma-1} - 1)(r_p - 1)]}{(\gamma - 1)(r - 1)}$$
$$= \frac{1 \times 8 [(8)^{1.4-1} - 1] (1.36 - 1)}{(1.4 - 1)(8 - 1)} \quad \dots [\text{Eqn. (21.6)}] \quad \text{or}$$
$$= \frac{8 (2.297 - 1)(0.36)}{0.4 \times 7} = 1.334 \text{ bar}$$

Hence mean effective pressure = **1.334 bar. (Ans.)**

Question

The minimum pressure and temperature in an Otto cycle are 100 kPa and 27°C. The amount of heat added to the air per cycle is 1500 kJ/kg.

(i) Determine the pressures and temperatures at all points of the air standard Otto cycle.

(ii) Also calculate the specific work and thermal efficiency of the cycle for a compression ratio of 8 : 1.

Take for air : $c_v = 0.72 \text{ kJ/kg K}$, and $\gamma = 1.4$.

Solution. Refer to Fig. 21.7. Given : $p_1 = 100 \text{ kPa} = 10^5 \text{ N/m}^2$ or 1 bar ;

$T_1 = 27 + 273 = 300 \text{ K}$; Heat added = 1500 kJ/kg ;

$r = 8 : 1$; $c_v = 0.72 \text{ kJ/kg}$; $\gamma = 1.4$.

Consider 1 kg of air.

Consider 1 kg of air.

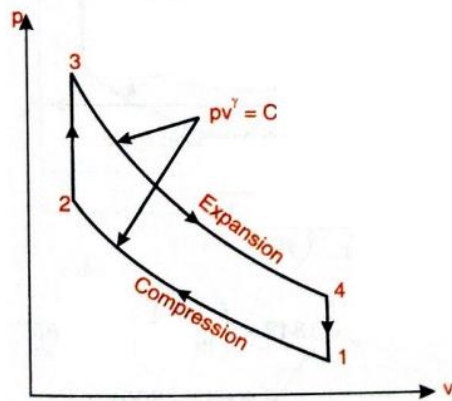


Fig. 21.7

(i) Pressures and temperatures at all points :

Adiabatic compression process 1-2 :

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1} = (r)^{\gamma-1} = (8)^{1.4-1} = 2.297$$

$$T_2 = 300 \times 2.297 = 689.1 \text{ K. (Ans.)}$$

Also $p_1 v_1^\gamma = p_2 v_2^\gamma$

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2} \right)^\gamma = (8)^{1.4} = 18.379$$

$$\therefore p_2 = 1 \times 18.379 = 18.379 \text{ bar. (Ans.)}$$

Constant volume process 2-3 :

Heat added during the process,

$$c_v (T_3 - T_2) = 1500$$

or $0.72 (T_3 - 689.1) = 1500$

or $T_3 = \frac{1500}{0.72} + 689.1 = 2772.4 \text{ K. (Ans.)}$

Also, $\frac{p_2}{T_2} = \frac{p_3}{T_3} \Rightarrow p_3 = \frac{p_2 T_3}{T_2}$

$$= \frac{18.379 \times 2772.4}{689.1} = 73.94 \text{ bar. (Ans.)}$$

Adiabatic Expansion process 3-4 :

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3} \right)^{\gamma-1} = (r)^{\gamma-1} = (8)^{1.4-1} = 2.297$$

$$\therefore T_4 = \frac{T_3}{2.297} = \frac{2772.4}{2.297} = \mathbf{1206.9 \text{ K. (Ans.)}}$$

$$\begin{aligned} \text{Also, } p_3 v_3^\gamma &= p_4 v_4^\gamma \Rightarrow p_4 = p_3 \times \left(\frac{v_3}{v_4} \right)^\gamma \\ &= 73.94 \times \left(\frac{1}{8} \right)^{1.4} = \mathbf{4.023 \text{ bar. (Ans.)}} \end{aligned}$$

(ii) Specific work and thermal efficiency :

$$\begin{aligned} \text{Specific work} &= \text{Heat added} - \text{heat rejected} \\ &= c_v (T_3 - T_2) - c_v (T_4 - T_1) = c_v [(T_3 - T_2) - (T_4 - T_1)] \\ &= 0.72 [(2772.4 - 689.1) - (1206.9 - 300)] \\ &= \mathbf{847 \text{ kJ/kg. (Ans.)}} \end{aligned}$$

$$\text{Thermal efficiency, } \eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}}$$

Question

A certain quantity of air at a pressure of 1 bar and temperature of 70°C is compressed adiabatically until the pressure is 7 bar in Otto cycle engine. 465 kJ of heat per kg of air is now added at constant volume. Determine:

- (i) *Compression ratio of the engine.*
- (ii) *Temperature at the end of compression.*
- (iii) *Temperature at the end of heat addition.*

Initial pressure, $p_1 = 1 \text{ bar}$

Initial temperature, $T_1 = 70 + 273 = 343 \text{ K}$

Pressure after adiabatic compression,

$$p_2 = 7 \text{ bar}$$

Heat addition at constant volume,

$$Q_s = 465 \text{ kJ/kg of air}$$

Specific heat at constant pressure,

$$c_p = 1.0 \text{ kJ/kg K}$$

Specific heat at constant volume,

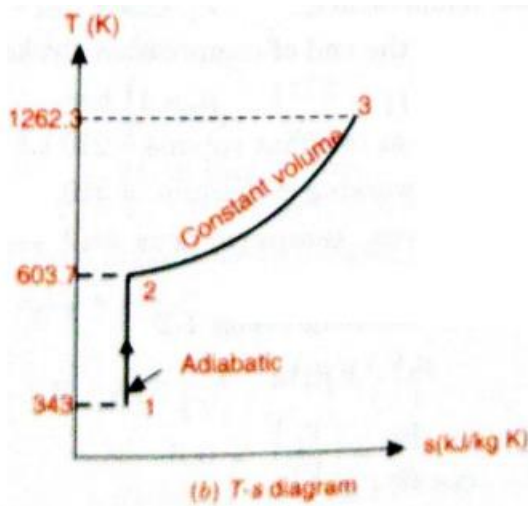
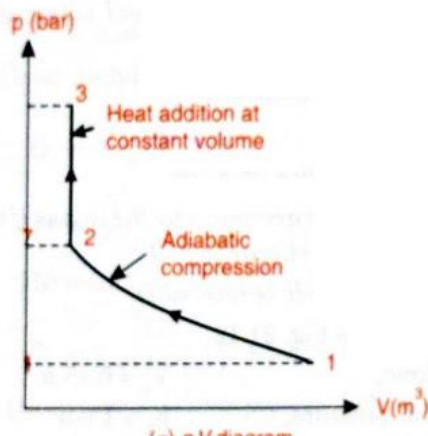
$$c_v = 0.706 \text{ kJ/kg K}$$

$$\gamma = \frac{c_p}{c_v} = \frac{1.0}{0.706} = 1.41$$

(i) Compression ratio of engine, r :

According to adiabatic compression 1-2

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



$$\begin{aligned} \text{or} \quad \left(\frac{V_1}{V_2} \right)^\gamma &= \frac{p_2}{p_1} & \text{or} \\ \text{or} \quad (r)^\gamma &= \frac{p_2}{p_1} & \left(\because \frac{V_1}{V_2} = r \right) & \text{or} \end{aligned}$$

or

$$r = \left(\frac{p_2}{p_1} \right)^{\frac{1}{\gamma}} = \left(\frac{7}{1} \right)^{\frac{1}{1.41}} = (7)^{0.709} = 3.97$$

Hence compression ratio of the engine = **3.97**. (Ans.)

(ii) Temperature at the end of compression, T_2 :

In case of adiabatic compression 1-2,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma-1} = (3.97)^{1.41-1} = 1.76$$

$$\therefore T_2 = 1.76 T_1 = 1.76 \times 343 = 603.7 \text{ K or } 330.7^\circ\text{C}$$

Hence temperature at the end of compression = **330.7°C**. (Ans.)

(iii) Temperature at the end of heat addition, T_3 :

According to constant volume heating operation 2-3

$$Q_s = c_v (T_3 - T_2) = 465$$

$$0.706 (T_3 - 603.7) = 465$$

$$\text{or } T_3 - 603.7 = \frac{465}{0.706}$$

$$\text{or } T_3 = \frac{465}{0.706} + 603.7 = 1262.3 \text{ K or } 989.3^\circ\text{C}$$

Hence temperature at the end of heat addition = **989.3°C**. (Ans.)

Question

.In a constant volume 'Otto cycle', the pressure at the end of compression is 15 times that at the start, the temperature of air at the beginning of compression is 38°C and maximum temperature attained in the cycle is 1950°C . Determine :

(i) Compression ratio.

(ii) Thermal efficiency of the cycle.

(iii) Work done.

Take γ for air = 1.4.

Solution.

Initial temperature, $T_1 = 38 + 273 = 311 \text{ K}$

Maximum temperature, $T_3 = 1950 + 273 = 2223 \text{ K}$.

(i) Compression ratio, r :

For adiabatic compression 1-2,

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

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

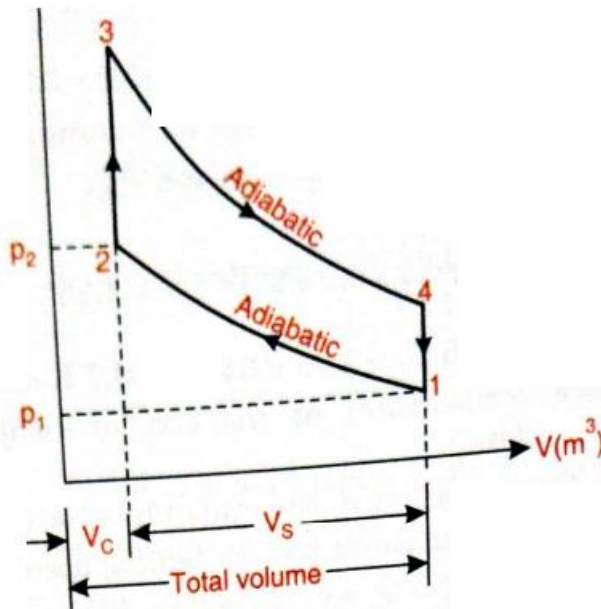
But
$$\frac{p_2}{p_1} = 15 \quad \dots(\text{given})$$

$$\therefore (r)^\gamma = 15 \quad \left[\because r = \frac{V_1}{V_2} \right]$$

or
$$(r)^{1.4} = 15$$

or
$$r = (15)^{\frac{1}{1.4}} = (15)^{0.714} = 6.9$$

Hence compression ratio = **6.9. (Ans.)**



(ii) Thermal efficiency :

Thermal efficiency,
$$\eta_{th} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(6.9)^{1.4-1}}$$

$$= 0.538 \text{ or } 53.8\%. \quad (\text{Ans.})$$

iii) Work done :

Again, for adiabatic compression 1-2,

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

$$= (6.9)^{1.4-1} = (6.9)^{0.4} = 2.16$$

$$T_2 = T_1 \times 2.16 = 311 \times 2.16 = 671.7 \text{ K or } 398.7^\circ\text{C}$$

For adiabatic expansion process 3–4

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3} \right)^{\gamma-1} = (r)^{\gamma-1} = (6.9)^{0.4} = 2.16$$

or $T_4 = \frac{T_3}{2.16} = \frac{2223}{2.16} = 1029 \text{ K or } 756^\circ\text{C}$

Heat supplied per kg of air

$$\begin{aligned} &= c_v(T_3 - T_2) = 0.717(2223 - 671.7) \\ &= 1112.3 \text{ kJ/kg or air} \end{aligned}$$

$$\left[c_v = \frac{R}{\gamma - 1} = \frac{0.287}{1.4 - 1} \right] \\ = 0.717 \text{ kJ/kg K}$$

Heat rejected per kg of air

$$\begin{aligned} &= c_v(T_4 - T_1) = 0.717(1029 - 311) \\ &= 514.8 \text{ kJ/kg of air} \end{aligned}$$

∴ Work done per kg of air

$$\begin{aligned} &= \text{Heat supplied} - \text{heat rejected} \\ &= 1112.3 - 514.8 \\ &= 597.5 \text{ kJ or } 597500 \text{ Nm. (Ans.)} \end{aligned}$$

Question

An engine working on Otto cycle has a volume of 0.45 m^3 , pressure 1 bar and temperature 30°C at the beginning of compression stroke. At the end of compression stroke, the pressure is 11 bar. 210 kJ of heat is added at constant volume. Determine :

(i) Pressures, temperatures and volumes at salient points in the cycle.

(ii) Percentage clearance.

(iii) Efficiency.

(iv) Mean effective pressure.

(v) Ideal power developed by the engine if the number of working cycles per minute is 210.

Assume the cycle is reversible.

Solution.

Volume,	$V_1 = 0.45 \text{ m}^3$
Initial pressure,	$p_1 = 1 \text{ bar}$
Initial temperature,	$T_1 = 30 + 273 = 303 \text{ K}$
Pressure at the end of compression stroke,	$p_2 = 11 \text{ bar}$
Heat added at constant volume =	210 kJ
Number of working cycles/min. =	210.

(i) Pressures, temperatures and volumes at salient points :

For adiabatic compression 1-2

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

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

or
$$r = \left(\frac{p_2}{p_1} \right)^{\frac{1}{\gamma}} = \left(\frac{11}{1} \right)^{\frac{1}{1.4}} = (11)^{0.714} = 5.5$$

Also
$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma-1} = (r)^{\gamma-1} = (5.5)^{1.4-1}$$

$$= 1.977 \approx 1.98$$

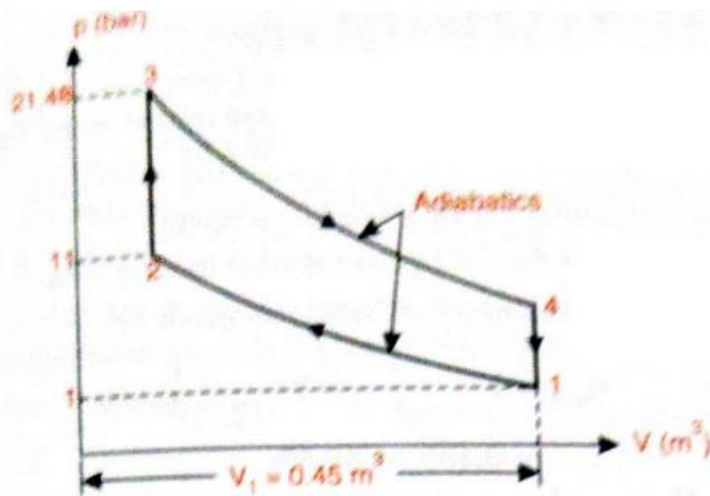


Fig. 21.12

$\therefore T_2 = T_1 \times 1.98 = 303 \times 1.98 = 600 \text{ K. (Ans.)}$

Applying gas laws to points 1 and 2

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

$\therefore V_2 = \frac{T_2}{T_1} \times \frac{p_1}{p_2} \times V_1 = \frac{600 \times 1 \times 0.45}{303 \times 11}$
 $= 0.081 \text{ m}^3. \text{ (Ans.)}$

The heat supplied during the process 2-3 is given by :

$$Q_s = m c_v (T_3 - T_2)$$

where $m = \frac{p_1 V_1}{RT_1} = \frac{1 \times 10^5 \times 0.45}{287 \times 303} = 0.517 \text{ kg}$

$\therefore 210 = 0.517 \times 0.71 (T_3 - 600)$

or
$$T_3 = \frac{210}{0.517 \times 0.71} + 600 = 1172 \text{ K. (Ans.)}$$

For the *constant volume process 2-3*

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

$$p_3 = \frac{T_3}{T_2} \times p_2 = \frac{1172}{600} \times 11$$
$$= \mathbf{21.48 \text{ bar. (Ans.)}}$$

$$V_3 = V_2 = \mathbf{0.081 \text{ m}^3. \text{ (Ans.)}}$$

For the *adiabatic (or isentropic) process 3-4*

$$p_3 V_3^\gamma = p_4 V_4^\gamma$$

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

$$= 21.48 \times \left(\frac{1}{5.5} \right)^{1.4} = \mathbf{1.97 \text{ bar. (Ans.)}}$$

$$\text{Also } \frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma-1} = \left(\frac{1}{r} \right)^{\gamma-1} = \left(\frac{1}{5.5} \right)^{1.4-1} = 0.505$$

$$\therefore T_4 = 0.505 T_3 = 0.505 \times 1172 = \mathbf{591.8 \text{ K. (Ans.)}}$$

$$V_4 = V_1 = \mathbf{0.45 \text{ m}^3. \text{ (Ans.)}}$$

(ii) Percentage clearance :

Percentage clearance

$$= \frac{V_c}{V_s} = \frac{V_2}{V_1 - V_2} \times 100 = \frac{0.081}{0.45 - 0.081} \times 100$$
$$= \mathbf{21.95\%. (Ans.)}$$

(iii) Efficiency :

The heat rejected per cycle is given by

$$Q_r = mc_v(T_4 - T_1)$$
$$= 0.517 \times 0.71 (591.8 - 303) = 106 \text{ kJ}$$

The air-standard efficiency of the cycle is given by

$$\eta_{\text{otto}} = \frac{Q_s - Q_r}{Q_s} = \frac{210 - 106}{210}$$
$$= \mathbf{0.495 \text{ or } 49.5\%. (Ans.)}$$

Alternatively :

$$\eta_{\text{otto}} = 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(5.5)^{1.4-1}}$$
$$= \mathbf{0.495 \text{ or } 49.5\%. (Ans.)}$$