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ME1251 THERMAL ENGINEERING

UNIT I

GAS POWER CYCLES

CONTENTS

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TECHNICAL TERMS:

1. **Gas Power Cycles:**

   Working fluid remains in the gaseous state through the cycle. Sometimes useful to study an idealised cycle in which internal irreversibilities and complexities are removed. Such cycles are called:Air Standard Cycles

2. **The mean effective pressure (MEP)**

   A fictitious pressure that, if it were applied to thepiston during the power stroke, would producethe same amount of net work as that produced during the actual cycle.

3. **Thermodynamics:**

   is the science of the relations between heat ,work and the properties of system

4. **Boundary:**

   System is a fixed and identifiable collection of matter enclosed by a real or imaginary surface which is impermeable to matter but which may change its shape or volume. The surface is called the boundary

5. **Surroundings:**

   Everything outside the system which has a direct bearing on the system's behaviour.

6. **ExtensivePropety:**

   Extensive properties are those whose value is the sum of the values for each subdivision of the system, eg mass, volume.

7. **IntensivePropety:**

   Properties are those which have a finite value as the size of the system approaches zero, *eg pressure, temperature, etc.*

8. **Equilibrium:**

   A system is in thermodynamic equilibrium if no tendency towards spontaneous change

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exists within the system. Energy transfers across the system disturb the equilibrium state of the system but may not shift the system significantly from its equilibrium state if carried out at low rates of change. I mentioned earlier that to define the properties of a system, they have to be uniform throughout the system.

Therefore to define the state of system, the system must be in equilibrium. (Inequilibrium of course implies non-uniformity of one or more properties).

9. **Process:**

A process is the description of what happens when a system changes its state by going through a succession of equilibrium states.

10. **Cyclic Process:**

A cyclic process is one for which the initial and final states of the system are identical.

11. **Isentropic process:**

is one in which for purposes of engineering analysis and calculation, one may assume that the process takes place from initiation to completion without an increase or decrease in the entropy of the system, i.e., the entropy of the system remains constant.

12. **Isentropic flow:**

An **isentropic flow** is a flow that is both adiabatic and reversible. That is, no heat is added to the flow, and no energy transformations occur due to friction or dissipative effects. For an isentropic flow of a perfect gas, several relations can be derived to define the pressure, density and temperature along a streamline.

13. **Adiabatic heating**

Adiabatic heating occurs when the pressure of a gas is increased from work done on it by its surroundings, e.g. a piston. Diesel engines rely on adiabatic heating during their compression

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14. **Adiabatic cooling:**

Adiabatic cooling occurs when the pressure of a substance is decreased as it does work on its surroundings. Adiabatic cooling occurs in the Earth's atmosphere with orographic lifting and lee waves,When the pressure applied on a parcel of air decreases, the air in the parcel is allowed to expand; as the volume increases, the temperature falls and internal energy decreases

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UNIT-I

GAS POWER CYCLES

1.1 The Otto Cycle

The Otto cycle, which was first proposed by a Frenchman, Beau de Rochas in 1862, was first used on an engine built by a German, Nicholas A. Otto, in 1876. The cycle is also called a constant volume or explosion cycle. This is the equivalent air cycle for reciprocating piston engines using spark ignition. Figures 1 and 2 show the P-V and T-s diagrams respectively.

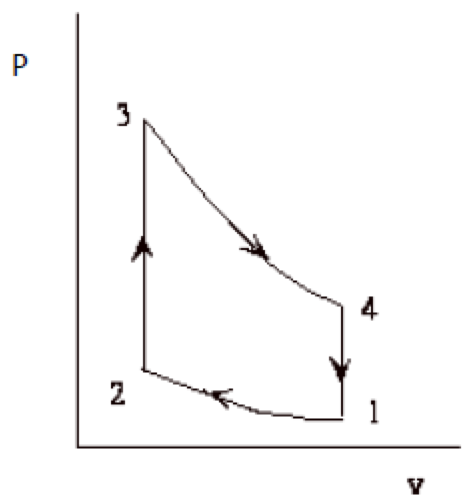

Fig 1.1 P-V Diagram of Otto Cycle.

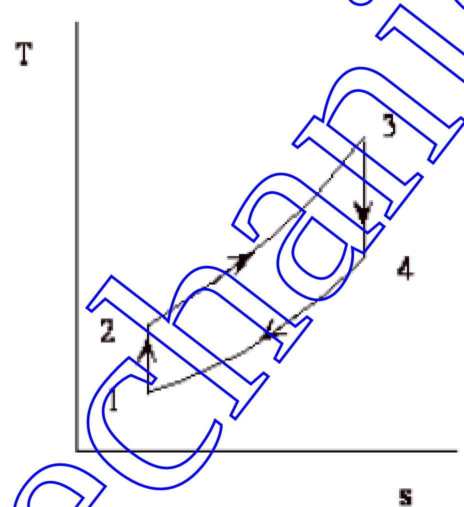

Fig 1.2 T-S Diagram of Otto Cycle.

At the start of the cycle, the cylinder contains a mass M of air at the pressure and volume indicated at point 1. The piston is at its lowest position. It moves upward and the gas is compressed isentropic ally to point 2. At this point, heat is added at constant volume which raises the pressure to point 3. The high pressure charge now expands isentropic ally, pushing the piston down on its expansion stroke to point 4 where the charge rejects heat at constant volume to the initial state, point .

The isothermal heat addition and rejection of the Carnot cycle are replaced by the constant volume processes which are, theoretically more plausible, although in practice, even these processes are not practicable.

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The heat supplied, Q_s, per unit mass of charge, is given by

$$c_v(T_3 - T_2)$$

The heat rejected, Q_r per unit mass of charge is given by

$$c_v(T_4 - T_1)$$

and the thermal efficiency is given by

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

$$\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T_1}{T_2}\left\{\frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)}\right\}$$

$$\text{Now } \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \frac{T_4}{T_3}$$

$$\text{And since } \frac{T_1}{T_2} = \frac{T_4}{T_3} \quad \text{we have} \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

Hence, substituting in Eq. 3, we get, assuming that r is the compression ratio V1/V2

$$\eta_{th} = 1 - \frac{T_1}{T_2}$$

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

$$= 1 - \frac{1}{r^{\gamma-1}}$$

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In a true thermodynamic cycle, the term expansion ratio and compression ratio are synonymous. However, in a real engine, these two ratios need not be equal because of the valve timing and therefore the term expansion ratio is preferred sometimes.

Equation 4 shows that the thermal efficiency of the theoretical Otto cycle increases with increase in compression ratio and specific heat ratio but is independent of the heat added (independent of load) and initial conditions of pressure, volume and temperature.

Mean effective pressure and air standard efficiency

It is seen that the air standard efficiency of the Otto cycle depends only on the compression ratio. However, the pressures and temperatures at the various points in the cycle and the net work done, all depend upon the initial pressure and temperature and the heat input from point 2 to point 3, besides the compression ratio.

A quantity of special interest in reciprocating engine analysis is the
mean effective pressure. Mathematically, it is the net work done on the piston, W, divided by the piston displacement volume, $V_1 - V_2$. This quantity has the units of pressure. Physically, it is that constant pressure which, if exerted on the piston for the whole outward stroke, would yield work equal to the work of the cycle. It is given by

Mean Effective Pressure (Pm) = $P_1 \, r \frac{[(k-1)(r^{\gamma-1}-1)]}{[(\gamma-1)(r-1)]}$

$$mep = \frac{W}{V_1 - V_2}$$

$$= \frac{\eta Q_{2-3}}{V_1 - V_2}$$

where Q2-3 is the heat added from points 2 to 3. Work done per kg of air

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$$W = \frac{P_3V_3 - P_4V_4}{\nu - 1} - \frac{P_2V_2 - P_1V_1}{\nu - 1} = mepV_s = P_m(V_1 - V_2)$$

$$mep = \frac{1}{(V_1 - V_2)}\left[\frac{P_3V_3 - P_4V_4}{\nu - 1} - \frac{P_2V_2 - P_1V_1}{\nu - 1}\right]$$

The pressure ratio P3/P2 is known as explosion ratio rp

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\nu} = r^{\nu} \Rightarrow P_2 = P_1 r^{\nu},$$

$$P_3 = P_2 r_p = P_1 r^{\nu} r_p,$$

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{\nu} = P_1 r^{\nu} r_p \left(\frac{V_2}{V_1}\right)^{\nu} = P_1 r_p$$

$$\frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = r$$

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

Substituting the above values in Eq 5A

$$mep = P_1 \frac{r(r_p - 1)(r^{\gamma - 1} - 1)}{(r - 1)(\gamma - 1)}$$

$$V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right)$$

$$= V_1\left(1 - \frac{1}{r}\right)$$

Here r is the compression ratio,

V1/V2 From the equation of state:

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$$V_1 = M\frac{R_0}{m}\frac{T_1}{p_1}$$

R0 is the universal gas constant Substituting for V1 and for V1 – V2 ,

$$mep = \eta\frac{Q_{2-3}\dfrac{p_1 m}{MR_0T_1}}{1-\dfrac{1}{r}}$$

The quantity Q2-3/M is the heat added between points 2 and 3 per unit mass of air (M is the mass of air and m is the molecular weight of air); and is denoted by Q‟, thus

$$mep = \eta\frac{Q'\dfrac{p_1 m}{R_0T_1}}{1-\dfrac{1}{r}}$$

We can non-dimensionalize the mep by dividing it by p1 so that we can obtain the following equation

$$\frac{mep}{p_1} = \eta\left[\frac{1}{1-\dfrac{1}{r}}\right]\left[\frac{Q'm}{R_0T_1}\right]$$

Since $\dfrac{R_0}{m} = c_v(\gamma-1)$, we can substitute it in Eq. 25 to get

$$\frac{mep}{p_1} = \eta\frac{Q'}{c_vT_1}\frac{1}{\left[1-\dfrac{1}{r}\right][\gamma-1]}$$

The dimensionless quantity mep/p1 is a function of the heat added, initial temperature, compression ratio and the properties of air, namely, cv and γ. We see that the mean effective pressure is directly proportional to the heat added and inversely proportional to the initial (or ambient) temperature. We can substitute the value of η from Eq. 8 in Eq. 14 and obtain the value

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of mep/p1 for the Otto cycle in terms of the compression ratio and heat added. In terms of the pressure ratio, p3/p2 denoted by rp we could obtain the value of mep/p1 as follows:

$$\frac{mep}{p_1} = \frac{r(r_p - 1)(r^{\gamma - 1} - 1)}{(r-1)(\gamma - 1)}$$

We can obtain a value of rp in terms of Q‟ as follows:

$$r_p = \frac{Q'}{c_v T_1 r^{\gamma - 1}} + 1$$

Choice of Q'

We have said that,

$$Q' = \frac{Q_{2-3}}{M}$$

M is the mass of charge (air) per cycle, kg.

Now, in an actual engine

$$Q_{2-3} = M_f Q_c$$

$$= FM_a Q_c \ in \ kJ/cycle$$

Mf is the mass of fuel supplied per cycle, kg

Qc is the heating value of the fuel, Kj/kg

Ma is the mass of air taken in per cycle

F is the fuel air ratio = Mf/Ma

Substituting,

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$$Q' = \frac{FM_a Q_c}{M}$$

$$Now \quad \frac{M_a}{M} \approx \frac{V_1 - V_2}{V_1}$$

$$And \quad \frac{V_1 - V_2}{V_1} = 1 - \frac{1}{r}$$

So, substituting for Ma/M

$$Q' = FQ_c\left(1 - \frac{1}{r}\right)$$

For isooctane, FQc at stoichiometric conditions is equal to 2975 KJ/kg, thus

Q' = 2975(r – 1)/r

At an ambient temperature, T1 of 300K and Cv for air is assumed to be 0.718 KJ/kgK, we get a value of Q‟/cvT1 = 13.8(r – 1)/r.

Under fuel rich conditions, φ = 1.2, Q‟/ cvT1 = 16.6(r – 1)/r

Under fuel lean conditions, φ = 0.8, Q‟/ cvT1 = 11.1(r – 1)/r

1.2 Diesel Cycle

This cycle, proposed by a German engineer, Dr. Rudolph Diesel to describe the processes of his engine, is also called the constant pressure cycle. This is believed to be the equivalent air cycle for the reciprocating slow speed compression ignition engine. The P -V and T-s diagrams are shown in Figs 4 and 5 respectively.

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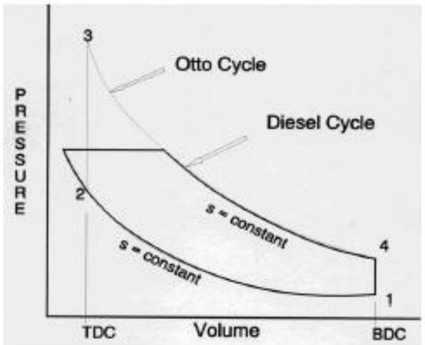

Fig 1.3 **P-V Diagram of Diesel Cycle.**

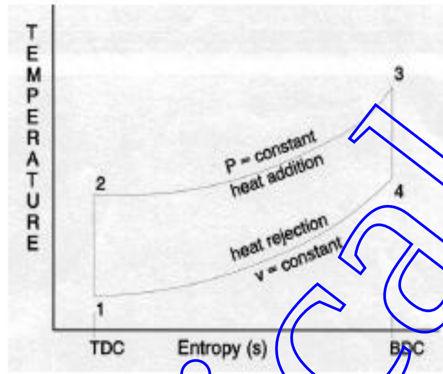

Fig 1.4 **T-S Diagram of Diesel Cycle.**

The cycle has processes which are the same as that of the Otto cycle except that the heat is added at constant pressure. The heat supplied, Qs is given by Cp(T3 – T2)

Whereas the heat rejected, Qr is given by Cv(T4 – T1)

And the thermal efficiency is given by

$$\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)}$$

$$= 1 - \frac{1}{\gamma}\left\{\frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}\right\}$$

From the T-s diagram, Fig. 5, the difference in enthalpy between points 2 and 3 is the same as that between 4 and 1, thus

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$$\Delta s_{2-3} = \Delta s_{4-1}$$

$$\therefore c_v \ln\left(\frac{T_4}{T_1}\right) = c_p \ln\left(\frac{T_3}{T_2}\right)$$

$$\therefore \ln\left(\frac{T_4}{T_1}\right) = \gamma \ln\left(\frac{T_3}{T_2}\right)$$

$$\therefore \frac{T_4}{T_1} = \left(\frac{T_3}{T_2}\right)^{\gamma} \text{ and } \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \frac{1}{r^{\gamma-1}}$$

Substituting in eq.

$$\eta_{th} = 1 - \frac{1}{\gamma}\left(\frac{1}{r}\right)^{\gamma-1}\left[\frac{\left(\frac{T_3}{T_2}\right)^{\gamma} - 1}{\frac{T_3}{T_2} - 1}\right]$$

$$\text{Now } \frac{T_3}{T_2} = \frac{V_3}{V_2} = r_c = cut-off\ ratio$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}\right] \qquad (26)$$

When Eq. 26 is compared with Eq. 8, it is seen that the expressions are similar except for the term in the parentheses for the Diesel cycle. It can be shown that this term is always greater than unity.

Now $r_c = \frac{V_3}{V_2} = \frac{V_3}{V_4} \Big/ \frac{V_2}{V_1} = \frac{r}{r_e}$ where r is the compression ratio and r_e is the expansion ratio

Thus, the thermal efficiency of the Diesel cycle can be written as

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$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\left(\frac{r}{r_e}\right)^{\gamma} - 1}{\gamma\left(\frac{r}{r_e} - 1\right)}\right]$$

Let re = r – Δ since r is greater than re. Here, Δ is a small quantity. We therefore have

$$\frac{r}{r_e} = \frac{r}{r - \Delta} = \frac{r}{r\left(1 - \frac{\Delta}{r}\right)} = \left(1 - \frac{\Delta}{r}\right)^{-1}$$

We can expand the last term binomially so that

$$\left(1 - \frac{\Delta}{r}\right)^{-1} = 1 + \frac{\Delta}{r} + \frac{\Delta^2}{r^2} + \frac{\Delta^3}{r^3} + \cdots$$

$$\text{Also } \left(\frac{r}{r_e}\right)^{\gamma} = \frac{r^{\gamma}}{(r-\Delta)^{\gamma}} = \frac{r^{\gamma}}{r^{\gamma}\left(1 - \frac{\Delta}{r}\right)^{\gamma}} = \left(1 - \frac{\Delta}{r}\right)^{-\gamma}$$

$$\left(1 - \frac{\Delta}{r}\right)^{-\gamma} = 1 + \gamma\frac{\Delta}{r} + \frac{\gamma(\gamma+1)}{2!}\frac{\Delta^2}{r^2} + \frac{\gamma(\gamma+1)(\gamma+2)}{3!}\frac{\Delta^3}{r^3} + \cdots$$

Substituting in Eq. 27, we get

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\frac{\Delta}{r} + \frac{(\gamma+1)}{2!}\frac{\Delta^2}{r^2} + \frac{(\gamma+1)(\gamma+2)}{3!}\frac{\Delta^3}{r^3} + \cdots}{\frac{\Delta}{r} + \frac{\Delta^2}{r^2} + \frac{\Delta^3}{r^3} + \cdots}\right] \qquad (28)$$

Since the coefficients of $\frac{\Delta}{r}, \frac{\Delta^2}{r^2}, \frac{\Delta^3}{r^3},$ etc are greater than unity, the quantity in the brackets in Eq. 28 will be greater than unity. Hence, for the Diesel cycle, we subtract times a quantity greater than unity from one, hence for the same r, the Otto cycle efficiency is greater than that for a Diesel cycle.

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If $\frac{\Delta}{r}$ is small, the square, cube, etc of this quantity becomes progressively smaller, so the thermal efficiency of the Diesel cycle will tend towards that of the Otto cycle. From the foregoing we can see the importance of cutting off the fuel supply early in the forward stroke, a condition which, because of the short time available and the high pressures involved, introduces practical difficulties with high speed engines and necessitates very rigid fuel injection gear.

In practice, the diesel engine shows a better efficiency than the Otto cycle engine because the compression of air alone in the former allows a greater compression ratio to be employed. With a mixture of fuel and air, as in practical Otto cycle engines, the maximum temperature developed by compression must not exceed the self ignition temperature of the mixture; hence a definite limit is imposed on the maximum value of the compression ratio.

Thus Otto cycle engines have compression ratios in the range of 7 to 12 while diesel cycle engines have compression ratios in the range of 16 to 22.

$$mep = \frac{1}{V_s}\left[P_2(V_3 - V_2) + \frac{P_3V_3 - P_4V_4}{\nu - 1} - \frac{P_2V_2 - P_1V_1}{\nu - 1}\right] \qquad (29)$$

The pressure ratio P3/P2 is known as explosion ratio rp

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\nu} = r^{\nu} \Rightarrow P_2 = P_1 r^{\nu},$$

$$P_3 = P_2 = P_1 r^{\nu}$$

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{\nu} = P_1 r^{\nu}\left(\frac{V_2}{V_1}\right)^{\nu} = P_1 r_c^{\nu}$$

$$V_4 = V_1, V_2 = V_c,$$

$$\frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = r$$

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

Substituting the above values in Eq 29 to get Eq (29A) In terms of the cut-off ratio, we can obtain another expression for mep/p1 as follows

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$$mep = P_1 \frac{\gamma r^{\gamma}(r_c - 1) - r(r_c^{\gamma} - 1)}{(r-1)(\gamma - 1)} \qquad (29A)$$

We can obtain a value of rc for a Diesel cycle in terms of Q" as follows:

$$r_c = \frac{Q'}{c_p T_1 r^{\gamma - 1}} + 1 \qquad (30)$$

We can substitute the value of η from Eq. 38 in Eq. 26, reproduced below and obtain the value of mep/p1 for the Diesel cycle.

$$\frac{mep}{p_1} = \eta \frac{Q'}{c_v T_1} \frac{1}{\left[1 - \frac{1}{r}\right][\gamma - 1]}$$

For the Diesel cycle, the expression for mep/p3 is as follows:

$$\frac{mep}{p_3} = \frac{mep}{p_1}\left(\frac{1}{r^{\gamma}}\right) \qquad (31)$$

Modern high speed diesel engines do not follow the Diesel cycle. The process of heat addition is partly at constant volume and partly at constant pressure. This brings us to the dual cycle.

1.3. Solved Problems

1. In an Otto cycle air at 1bar and 290K is compressed isentropic ally until the pressure is 15bar The heat is added at constant volume until the pressure rises to 40bar. Calculate the air standard efficiency and mean effective pressure for the cycle. Take Cv=0.717 KJ/Kg K and R_{univ} = 8.314 KJ/Kg K.

GIVEN DATA:

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Pressure (P1) = 1bar = 100KN/m^2

Temperature(T1) = 290K

Pressure (P2) = 15bar = 1500KN/m^2

Pressure (P3) = 40bar = 4000KN/m^2

Cv = 0.717 KJ/KgK

R_{univ} = 8.314 KJ/Kg K

TO FIND:

i) Air Standard Efficiency (η_{otto})

ii) Mean Effective Pressure (P_m)

SOLUTION:

Here it is given R_{univ} = 8.314 KJ/Kg K

We know that ,

$\gamma = Cp/Cv$ (Here Cp is unknown)

$R_{univ} = M \, x \, R$

Since For air (O_2) molecular weight (M) = 28.97

8.314=28.97 *x* R

∴ R = 0.2869

(Since gas constant R = Cp-Cv)

0.2869 = Cp – 0.717

∴ Cp= 1.0039 KJ/Kg K

$$\gamma = \frac{Cp}{Cv} = \frac{1.0039}{0.717} = 1.4$$

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$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

$$\eta = 1 - \frac{1}{r^{1.4-1}}$$

Here 'r' is unknown.

We know that,

$$r = \left(\frac{V1}{V2}\right) = \left(\frac{P2}{P1}\right)^{\frac{1}{\gamma}}$$

$$= \left(\frac{1500}{100}\right)^{\frac{1}{1.4}}$$

$$\therefore\ r = 6.919$$

$$\eta_{otto} = 1 - \frac{1}{6.919^{0.4}}$$

$$\therefore\ \eta_{otto} = 53.87\%$$

Mean Effective Pressure (Pm) = $P_1\, r \frac{[(K-1)(r^{\gamma-1}-1)]}{[(\gamma-1)(r-1)]}$

Pm = $\frac{(100)(6.919)[(2.67-1)(6.919^{0.4}-1)]}{[(1.4-1)(6.919-1)]}$

Pm = 569.92 KN/m^2

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Problem 2

Estimate the lose in air standard efficiency for the diesel engine for the compression ratio 14 and the cutoff changes from 6% to 13% of the stroke.

Given Data

Case (i)	Case (i)
Compression ratio (r) = 14	compression ratio (r) =14
ρ = 6% Vs	ρ = 13%Vs

To Find

Lose in air standard efficiency.

Solution

Compression ratio (r) = $r = \frac{V1}{V2} = \frac{Vc+Vs}{Vc}$

$$14 = 1 + \frac{Vs}{Vc}$$

$$\frac{Vc}{Vs} = 13$$

Case (i):

Cutoff ratio (ρ) =V3/V2

$$\frac{V3}{V2} = \frac{Vc + 6\%Vs}{Vc}$$

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$$= 1 + \frac{6\%Vs}{Vc}$$

$$\rho = \frac{V3}{V2} = 1 + (0.06)(13)$$

ρ = 1.78

We know that,

$$\eta_{diesel} = 1 - \frac{1}{\gamma \times r^{\gamma-1}}\left[\frac{\rho^{\gamma}-1}{\rho-1}\right]$$

$$= 1 - \left(\frac{1}{(1.4)(14)^{1.4-1}}\right)\frac{[1.78^{1.4}-1]}{[1.78-1]}$$

$$= 1 - (0.2485)(1.5919)$$

$= 0.6043 \times 100\%$

$\eta_{diesel} = 60.43\%$

case (ii):

cutoff ratio $(\rho) = \frac{V3}{V2} = \frac{Vc+13\%Vs}{Vc}$

=1+(0.13) (13)

ρ = 2.69

$$\eta_{diesel} = 1 - \frac{1}{\gamma \times r^{\gamma-1}}\left[\frac{\rho^{\gamma}-1}{\rho-1}\right]$$

$$= 1 - \left(\frac{1}{(1.4)(14)^{1.4-1}}\right)\frac{[2.69^{1.4}-1]}{[2.69-1]}$$

= 1- (0.24855) (1.7729)

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$= 0.5593 \times 100\%$

$= 55.93\%$

Lose in air standard efficiency = $(\eta_{diesel\ CASE(i)}) - (\eta_{diesel\ CASE(i)})$

$= 0.6043 - 0.5593$

$= 0.0449$

$= 4.49\%$

Problem3

The compression ratio of an air standard dual cycle is 12 and the maximum pressure on the cycle is limited to 70bar. The pressure and temperature of the cycle at the beginning of compression process are 1bar and 300K. Calculate the thermal efficiency and Mean Effective Pressure. Assume cylinder bore = 250mm, Stroke length = 300mm, Cp=1.005KJ/Kg K, Cv=0.718KJ/Kg K.

Given data:

Assume $Qs_1 = Qs_2$

Compression ratio (r) = 12

Maximum pressure $(P_3) = (P_4) = 7000\ KN/m^2$

Temperature $(T_1) = 300K$

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Diameter (d) = 0.25m

Stroke length (l) = 0.3m

To find:

(i) Dual cycle efficiency (η_{dual})

(ii) Mean Effective Pressure (P_m)

Solution:

By Process 1-2:

$$\frac{T2}{T1} = \left[\frac{V2}{V1}\right]^{\gamma-1}$$

$$= [r]^{\gamma-1}$$

$$T2 = 300[12]^{1.4-1}$$

$$T_2 = 810.58K$$

$$\frac{P2}{P1} = \left[\frac{V1}{V2}\right]^{\gamma}$$

$$P2 = [12]^{1.4} \times 100$$

$$P_2 = 3242.3KN/m^2$$

By process 2-3:

$$\frac{P2}{T2} = \frac{P3}{T3}$$

$$\frac{P3}{P2} = \frac{T3}{T2}$$

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$$T3 = \left[\frac{7000}{3242.3}\right] 810.58$$

$T_3 = 1750K$

Assuming $Qs_1 = Qs_2$

mCv[T3-T2] = mCp[T4-T3]

0.718 [1750-810.58] = 1.005 [T4-1750]

$T_4 = 2421.15K$

By process 4-5:

$$\frac{T4}{T5} = \left[\frac{V5}{V4}\right]^{\gamma-1}$$

$$= \left[\frac{r}{\rho}\right]^{1.4-1}$$

We know that, $\rho = \frac{V4}{V3} = \frac{T4}{T3} = \frac{2421.15}{1750} = 1.38$

$$\frac{T4}{T5} = \left[\frac{12}{1.38}\right]^{0.4}$$

$$T5 = \frac{2421.15}{\left(\frac{12}{1.38}\right)^{0.4}}$$

$T_5 = 1019.3K$

Heat supplied $Q_s = 2\times m\ C_v \times [T3 - T2]$

$= 2 \times 1 \times 0.718 \times [1750 - 810.58]$

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$Q_s = 1349 KJ/Kg$

Heat rejected $Q_r = m\, C_v\, [T5 - T1]$

$Q_r = 516.45\ KJ/Kg$

$$\eta_{dual} = \frac{Q_s - Q_r}{Q_s} = \frac{832.55}{1349} \times 100$$

$\eta_{dual} = 61.72\%$

Stroke volume $(V_s) = \frac{\pi}{4} \times d^2 \times l$

$$= \frac{\pi}{4} \times 0.25^2 \times 0.3$$

$V_s = 0.0147 m^3$

Mean effective pressure $(p_m) = W/V_s$

$= 832.58/0.0147$

$P_m = 56535\ KN/m^2$

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1.4 Dual Cycle

P-V Diagram of Dual Cycle.

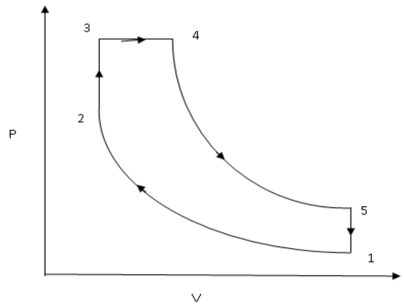

Fig 1.5 P-V Diagram

Process 1-2: Reversible adiabatic compression. Process 2-3: Constant volume heat addition. Process 3-4: Constant pressure heat addition. Process 4-5: Reversible adiabatic expansion. Process 5-1: Constant volume heat reject

T-S Diagram of Carnot Cycle.

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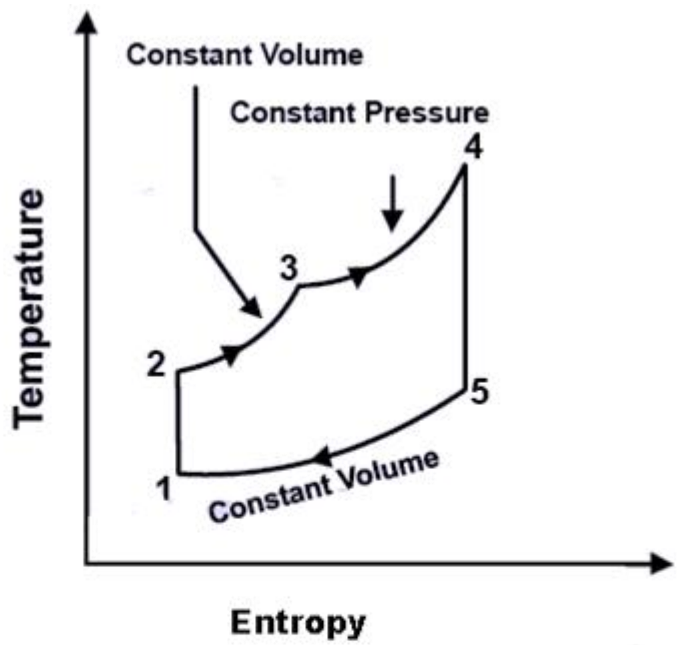

Fig 1.6 T-S Diagram

The cycle is the equivalent air cycle for reciprocating high speed compression ignition engines. The P-V and T-s diagrams are shown in Figs.6 and 7. In the cycle, compression and expansion processes are isentropic; heat addition is partly at constant volume and partly at constant pressure while heat rejection is at constant volume as in the case of the Otto and Diesel cycles.

The heat supplied, Qs per unit mass of charge is given by cv(T3 – T2) + cp(T3" – T2) (32)

whereas the heat rejected, Qr per unit mass of charge is given by cv(T4 – T1)

and the thermal efficiency is given by

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$$\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2) + c_p(T_{3'} - T_2)} \qquad (33A)$$

$$= 1 - \left\{ \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right) + \gamma T_3\left(\frac{T_{3'}}{T_3} - 1\right)} \right\} \qquad (33B)$$

$$= 1 - \frac{\frac{T_4}{T_1} - 1}{\frac{T_2}{T_1}\left(\frac{T_3}{T_2} - 1\right) + \frac{\gamma T_3}{T_2}\frac{T_2}{T_1}\left(\frac{T_{3'}}{T_3} - 1\right)} \qquad (33C)$$

From thermodynamics

$$\frac{T_3}{T_2} = \frac{p_3}{p_2} = r_p \qquad (34)$$

the explosion or pressure ratio and

$$\frac{T_{3'}}{T_3} = \frac{V_{3'}}{V_3} = r_c \qquad (35)$$

the cut-off ratio.

$$\text{Now, } \frac{T_4}{T_1} = \frac{p_4}{p_1} = \frac{p_4}{p_{3'}}\frac{p_{3'}}{p_3}\frac{p_3}{p_2}\frac{p_2}{p_1}$$

$$\text{Also } \frac{p_4}{p_{3'}} = \left(\frac{V_{3'}}{V_4}\right)^\gamma = \left(\frac{V_{3'}}{V_3}\frac{V_2}{V_1}\right)^\gamma = \left(r_c \frac{1}{r}\right)^\gamma$$

$$\text{And } \frac{p_2}{p_1} = r^\gamma$$

$$\text{Thus } \frac{T_4}{T_1} = r_p r_c^\gamma$$

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

Therefore, the thermal efficiency of the dual cycle is

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_p r_c^\gamma - 1}{(r_p - 1) + \gamma r_p (r_c - 1)}\right] \qquad (36)$$

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We can substitute the value of η from Eq. 36 in Eq. 14 and obtain the value of mep/p1 for the dual cycle.

In terms of the cut-off ratio and pressure ratio, we can obtain another expression for mep/p1 as follows:

$$\frac{mep}{p_1} = \frac{\gamma r_p r^{\gamma}(r_c - 1) + r^{\gamma}(r_p - 1) - r(r_p r_c^{\gamma} - 1)}{(r-1)(\gamma - 1)} \qquad (37)$$

For the dual cycle, the expression for mep/p3 is as follows:

$$\frac{mep}{p_3} = \frac{mep}{p_1}\left(\frac{p_1}{p_3}\right) \qquad (38)$$

Since the dual cycle is also called the limited pressure cycle, the peak pressure, p3, is usually specified. Since the initial pressure, p1, is known, the ratio p3/p1 is known. We can correlate rp with this ratio as follows:

$$r_p = \frac{p_3}{p_1}\left(\frac{1}{r^{\gamma}}\right) \qquad (39)$$

We can obtain an expression for rc in terms of Q‟ and rp and other known quantities as follows:

$$r_c = \frac{1}{\gamma}\left(\left[\left\{\frac{Q'}{c_v T_1 r^{\gamma-1}}\right\}\frac{1}{r_p}\right] + (\gamma - 1)\right) \qquad (40)$$

We can also obtain an expression for rp in terms of Q‟ and rc and other known quantities as follows:

$$r_p = \frac{\left[\frac{Q'}{c_v T_1 r^{\gamma-1}} + 1\right]}{1 + \gamma r_c - \gamma} \qquad (41)$$

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1.5 The Brayton Cycle

The Brayton cycle is also referred to as the Joule cycle or the gas turbine air cycle because all modern gas turbines work on this cycle. However, if the Brayton cycle is to be used for reciprocating piston engines, it requires two cylinders, one for compression and the other for expansion. Heat addition may be carried out separately in a heat exchanger or within the expander itself.

The pressure-volume and the corresponding temperature-entropy diagrams are shown in Figs 10 and 11 respectively.

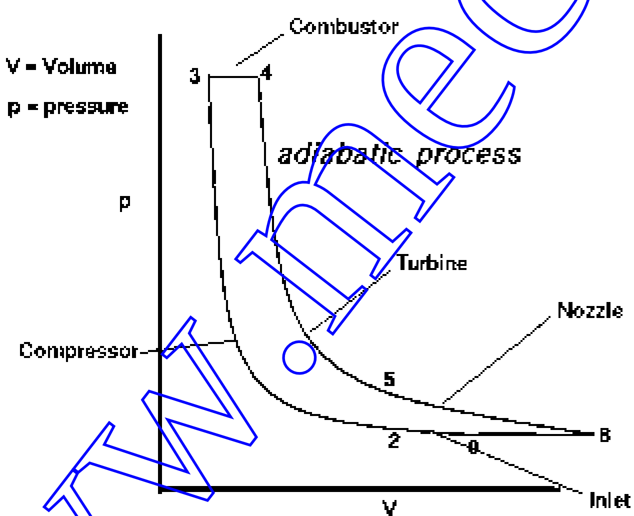

Fig 1.7 PV diagram Brayton Cycle

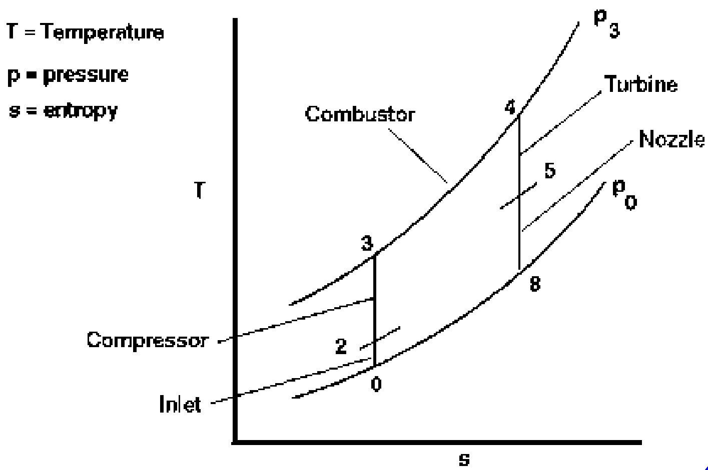

Fig 1.8 TS Diagram

The cycle consists of an isentropic compression process, a constant pressure heat addition process, an isentropic expansion process and a constant pressure heat rejection process. Expansion is carried out till the pressure drops to the initial (atmospheric) value.

Heat supplied in the cycle, Qs, is given by Cp(T3 – T2)

Heat rejected in the cycle, Qs, is given by Cp(T4 – T1)

Hence the thermal efficiency of the cycle is given by

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$$\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T_1}{T_2}\left\{\frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)}\right\} \qquad (42)$$

Now $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$

And since $\frac{T_2}{T_1} = \frac{T_3}{T_4}$ *we have* $\frac{T_4}{T_1} = \frac{T_3}{T_2}$

Hence, substituting in Eq. 62, we get, assuming that rp is the pressure ratio p2/p1

$$\eta_{th} = 1 - \frac{T_1}{T_2}$$

$$= 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}} \qquad (43)$$

This is numerically equal to the efficiency of the Otto cycle if we put

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

so that $\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}$ (43A) where r is the volumetric compression ratio.

1.6 Actual PV diagram of four stroke engine

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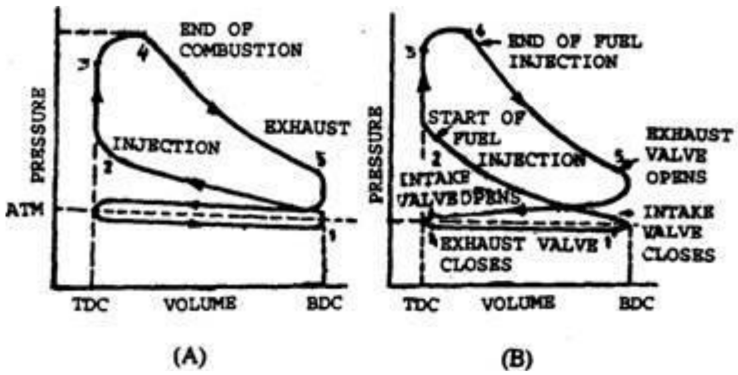

1.9 Actual PV diagram of four stroke engine

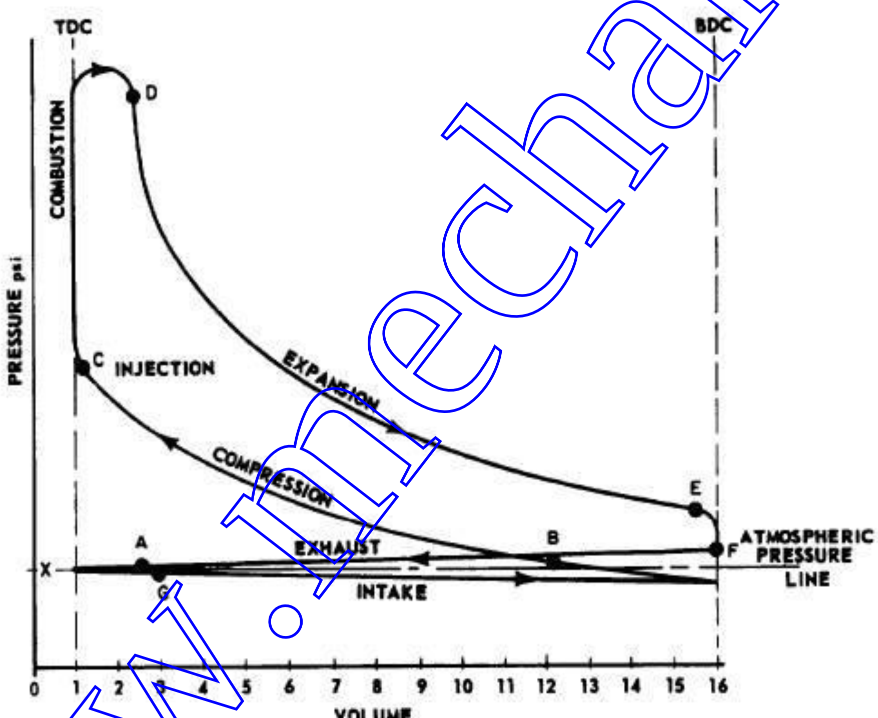

Fig 1.10Theoretical PV diagram for four stroke engine

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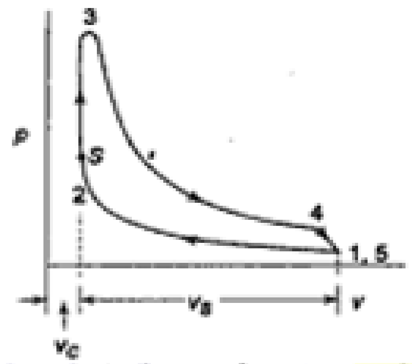
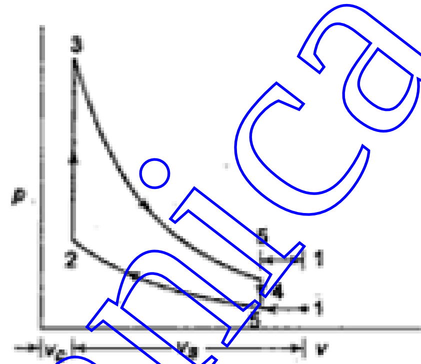


Actual p-v diagram for a two stroke petrol engine



Theoretical p-v diagram for two-stroke petrol engine v_c-clearance volume v_s-stroke volume 1-5 piston travel during open period

Fig 1.11 Theoretical and Actual PV diagram of two strokes Petrol Engine:

1.7 Solved Problems

4. The compression ratio of an air standard dual cycle is 12 and the maximum pressure on the cycle is limited to 70bar. The pressure and temperature of the cycle at the beginning of compression process are 1bar and 300K. Calculate the thermal efficiency and Mean Effective Pressure. Assume cylinder bore = 250mm, Stroke length = 300mm, Cp=1.005KJ/Kg K, Cv=0.718KJ/Kg K.

Given data:

Assume $Qs_1 = Qs_2$

Compression ratio (r) = 12

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Maximum pressure (P_3) = (P_4) = 7000 KN/m^2

Temperature (T_1) = 300K

Diameter (d) = 0.25m

Stroke length (l) = 0.3m

To find:

Dual cycle efficiency (η_{dual})

Mean Effective Pressure (P_m)

Solution:

By Process 1-2:

$$\frac{T2}{T1} = \left[\frac{V2}{V1}\right]^{\gamma-1}$$

$$= [r]^{\gamma-1}$$

$$T2 = 300[12]^{1.4-1}$$

$$T_2 = 810.58K$$

$$\frac{P2}{P1} = \left[\frac{V1}{V2}\right]^{\gamma}$$

$$P2 = [12]^{1.4} \times 100$$

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$$P2 = 3242.3 KN/m^2$$

By process 2-3:

$$\frac{P2}{T2} = \frac{P3}{T3}$$

$$\frac{P3}{P2} = \frac{T3}{T2}$$

$$T3 = \left[\frac{7000}{3242.3}\right] 810.58$$

$$T_3 = 1750K$$

Assuming $Qs_1 = Qs_2$

$$mCv[T3-T2] = mCp[T4-T3]$$

$$0.718\ [1750-810.58] = 1.005\ [T4-1750]$$

$$T_4 = 2421.15K$$

By process 4-5:

$$\frac{T4}{T5} = \left[\frac{V5}{V4}\right]^{\gamma-1}$$

$$= \left[\frac{r}{\rho}\right]^{1.4-1}$$

We know that, $\rho = \frac{V4}{V3} = \frac{T4}{T3} = \frac{2421.15}{1750} = 1.38$

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$$\frac{T4}{T5} = \left[\frac{12}{1.38}\right]^{0.4}$$

$$T5 = \frac{2421.15}{\left(\frac{12}{1.38}\right)^{0.4}}$$

T5 = 1019.3K

Heat supplied $Q_s = 2 \times m\, C_v \times [T3 - T2]$

$$= 2 \times 1 \times 0.718 \times [1750 - 810.58]$$

Q_s = 1349KJ/Kg

Heat rejected $Q_r = m\, C_v\, [T5 - T1]$

Q_r = 516.45 KJ/Kg

$$\eta_{dual} = \frac{Q_s - Q_r}{Q_s} = \frac{832.55}{1349} \times 100$$

η_{dual} = 61.72%

Stroke volume $(V_s) = \frac{\pi}{4} \times d^2 \times l$

$$= \frac{\pi}{4} \times 0.25^2 \times 0.3$$

$V_s = 0.0147 m^3$

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Mean effective pressure (p_m) = W/V_s

= 832.58/0.0147

P_m = 56535 KN/m^2

5. A diesel engine operating an air standard diesel cycle has 20cm bore and 30cmstroke.the clearance volume is 420cm^3.if the fuel is injected at 5% of the stroke,find the air standard efficiency.

Given Data:-

Bore diameter (d) =20cm=0.2mk

Stroke, (l) =30cm=0.3m

Clearance volume, (v_2) =420cm^3=420/100^3= $4.2 \times 10^{-4} m^3$

To Find:-

Air standard efficiency, (d_{iesel})

Solution:-

Compression ratio, $r = v_1/v_2$

$= (v_c+v_s)/v_c$

We know that,

Stroke volume, v_s=area*length

$= \left(\frac{\pi}{4}\right) d^2 \times l$

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$$=\left(\frac{\pi}{4}\right)(0.2^2)\times 0.3$$

$$V_s = 9.4\times10^{-3}\ m^3$$

Therefore,

Compression ratio, $(r) = \frac{4.2\times10^{-4} + 9.42\times10^{-3}}{4.2\times10^{-4}}$

$$r = 23.42$$

Cut off ratio, $\rho = v_3 / v_2$

$$= (v_c + 5\%\ v_s) / v_c$$

$$= 1 + (5\% v_s) / v_c$$

$$= 1 + \frac{(0.05\times 9.42\times10^{-3})}{4.2\times10^{-4}}$$

$$\rho = 2.12$$

We know the equation,

$$\eta_{diesel} = 1 - \left(\frac{1}{\gamma (r)^{\gamma-1}}\right)\times\left(\frac{\rho^{\gamma}-1}{\rho-1}\right)$$

$$= 1 - \frac{1}{1.4\times 23.42^{1.4-1}}\left(\frac{(2.12^{1.4}-1)}{2.12-1}\right)$$

$$= 1 - (0.20229)(1.6636)$$

$$= 0.6634\times 100$$

$$\eta_{diesel} = 66.34\%$$

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TWO MARK UNIVERSITY QUESTIONS:

1. What is a thermodynamic cycle?

2. What is meant by air standard cycle?

3. Name the various “gas power cycles".

4. What are the assumptions made for air standard cycle analysis

5. Mention the various processes of the Otto cycle.

6. Mention the various processes of diesel cycle.

7. Mention the various processes of dual cycle.

9. Define air standard cycle efficiency.

10. Define mean effective pressure as applied to gas power cycles. How it is related to indicate power of an I.C engine?

11. Define the following terms. (i) Compression ratio (ii) Cut off ratio, (iii) .Expansion ratio

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UNIVERSITY ESSAY QUESTIONS:

1. Drive and expression for the air standard efficiency of Otto cycle in terms of volume ratio. (16)

2. Drive an expression for the air standard efficiency of Diesel cycle. . (16)

3. Drive an expression for the air standard efficiency of Dual cycle. . (16)

4. Explain the working of 4 stroke cycle Diesel engine. Draw the theoretical and actual PV diagram.

5. Drive the expression for air standard efficiency of Brayton cycle in terms of pressure ratio.

6. A Dual combustion air standard cycle has a compression ratio of 10. The constant pressure part of combustion takes place at 40 bar. The highest and the lowest temperature of the cycle are 1725degree C and 27 0 C respectively. The pressure at the beginning of compression is 1 bar. Calculate (i) the pressure and temperature at' key points of the cycle. (ii) The heat supplied at constant volume, (iii) the heat supplied at constant pressure. (iv) The heat rejected. (v) The work output. (vi) The efficiency and (vii) mep. (16)

7. An Engine-working on Otto cycle has a volume of 0.45 m3 , pressure 1 bar and temperature 30o.C at the beginning of compression stroke. At the end of compression stroke, the pressure is 11 barand 210 KJ of heat is added at constant volume. Determine (i) Pressure, temperature and volumes at salient points in the cycle.' (ii) Efficiency.

8. Explain the working of 4-stroke cycle Diesel engine. Draw the theoretical and actual valve-timing diagram for the engine. Explain the reasons for the difference.

9. Air enters the compressor of a gas turbine at 100 KPa and 25 o C. For a pressure ratio of 5 and a maximum temperature of 850°C. Determine the thermal efficiency using the Brayton cycle. (16)

10. The following data in referred for an air standard diesel cycle compression ratio = 15 heat added= 200 Kj/Kg- minimum temperature in the cycle = 25°C Suction pressure = 1 bar Calculate 1. Pressure and temperature at the Salient point. 2. Thermal efficiency 3. Mean effective pressure, 4. Power output of the cycle, if flow rate 'of air is 2 Kg/s (16)

Sample Problems

1. A Dual combustion air standard cycle has a compression ratio of 10. The constant pressure part of combustion takes place at 40 bar. The highest and the lowest temperature of the cycle are 1727° C and 27° C respectivety.The pressure at the beginning of compression is 1 bar. Calculate- (i) The pressure and temperature at key points of the cycle. (ii) The heat supplied at constant volume, (iii) The heat supplied at constant pressure (iv) The heat rejected *(v)* The Work output, (vi) The efficiency and (vii) Mean effective pressure.

2. An Engine working on Otto cycle has a volume of 0.45 m3, pressure 1 bar and Temperature 30Oc, at the beginning of compression stroke. At the end of Compression stroke, the pressure is 11 bar and 210 KJ of heat is added at constant Volume.
Determine i. Pressure, temperature and volumes at salient points in the cycle. ii. Efficiency.

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