ME3451 THERMAL ENGINEERING

For IVth Semester

B.E. Mechanical Engineering course

As per the revised regulation of

ANNA University syllabus (2021 Regulation)

DEPARTMENT OF MECHANICAL ENGINEERING

ROHINI COLLEGE OF ENGINEERING AND TECHNOLOGY

ME3451 - THERMAL ENGINEERING

Syllabus

UNIT I THERMODYNAMIC CYCLES 12

Air Standard Cycles – Carnot, Otto, Diesel, Dual, and Brayton – Cycle Analysis, Performance and Comparison, Basic Rankine Cycle, modified, reheat and regenerative cycles.

UNIT II STEAM NOZZLES AND INJECTOR 12

Types and Shapes of nozzles, Flow of steam through nozzles, Critical pressure ratio, Variation of mass flow rate with pressure ratio. Effect of friction. Metastable flow.

UNIT III STEAM AND GAS TURBINES 12

Types, Impulse and reaction principles, Velocity diagrams, Work done and efficiency – optimal operating conditions. Multi-staging, compounding and governing. Gas turbine cycle analysis – open and closed cycle. Performance and its improvement - Regenerative, Intercooled, Reheated cycles and their combination.

UNIT IV INTERNAL COMBUSTION ENGINES – FEATURES AND COMBUSTION 12

IC engine – Classification, working, components and their functions. Ideal and actual : Valve and port timing diagrams, p-v diagrams- two stroke & four stroke, and SI & CI engines – comparison. Geometric, operating, and performance comparison of SI and CI engines. Desirable properties and qualities of fuels. Air-fuel ratio calculation – lean and rich mixtures. Combustion in SI & CI Engines – Knocking – phenomena and control.

UNIT V INTERNAL COMBUSTION ENGINE PERFORMANCE AND AUXILIARY SYSTEMS 12

Performance and Emission Testing, Performance parameters and calculations. Morse and Heat Balance tests. Multipoint Fuel Injection system and Common rail direct injection systems. Ignition systems – Magneto, Battery and Electronic. Lubrication and Cooling systems. Concepts of Supercharging and Turbocharging – Emission Norms

TOTAL: 60 PERIODS

TEXT BOOKS:

1. Mahesh. M. Rathore, “Thermal Engineering”, 1st Edition, Tata McGraw Hill, 2010.

2. Ganesan.V, “Internal Combustion Engines" 4th Edition, Tata McGraw Hill, 2012.

REFERENCES:

1. Ballaney. P, “Thermal Engineering”, 25th Edition, Khanna Publishers, 2017.

2. Domkundwar, Kothandaraman, & Domkundwar, “A Course in Thermal

UNIT – I

THERMODYNAMIC CYCLES

1. Derive air standard efficiency for an Otto cycle with the help of Pv diagram.

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

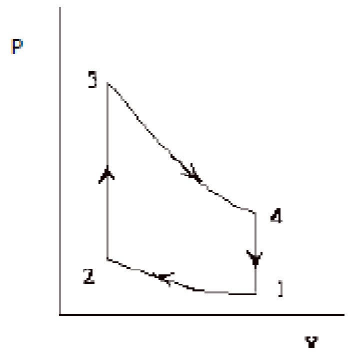


Fig.1: P-V Diagram of Otto Cycle.

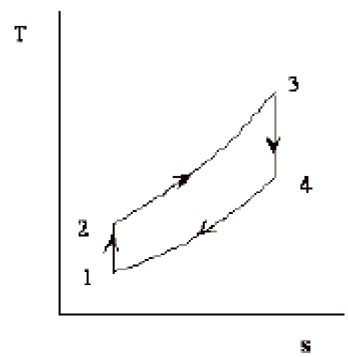


Fig.2: T-S Diagram of Otto Cycle.

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 1.

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.

The heat supplied, Qs, per unit mass of charge, is given by cv (T3 – T2) (1)

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

$$c_v(T_4 - T_1) \quad (2)$$

and the thermal efficiency is given by

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

$$= 1 - \frac{T_1}{T_2}\left\{\frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)}\right\} \qquad (3)$$

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

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

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

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

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

$$= 1 - \frac{1}{r^{\gamma-1}} \qquad (4)$$

2. Derive mean effective pressure expression for an Otto cycle

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

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

$$= \frac{\eta Q_{2-3}}{V_1 - V_2} \qquad (5)$$

where Q_{2-3} is the heat added from points 2 to 3.

Work done per kg of air

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

$$mep = \frac{1}{(V_1 - V_2)}\left[\frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1}\right] \qquad (5A)$$

The pressure ratio P_3/P_2 is known as explosion ratio r_p

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

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

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

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

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

Substituting the above values in Eq 5A

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

, Now

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

$$= V_1\left(1 - \frac{1}{r}\right) \qquad (6)$$

Here r is the compression ratio, V_1/V_2

From the equation of state:

$$V_1 = M\frac{R_0}{m}\frac{T_1}{p_1} \qquad (7)$$

R_0 is the universal gas constant

Substituting for V_1 and for $V_1 - V_2$,

$$mep = \eta \frac{Q_{2-3}\frac{p_1 m}{MR_0T_1}}{1 - \frac{1}{r}} \qquad (8)$$

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

$$mep = \eta \frac{Q' \frac{p_1 m}{R_0 T_1}}{1 - \frac{1}{r}} \quad (9)$$

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

$$\frac{mep}{p_1} = \eta \left[\frac{1}{1 - \frac{1}{r}} \right] \left[\frac{Q' m}{R_0 T_1} \right] \quad (10)$$

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

$$\frac{mep}{p_1} = \eta \frac{Q'}{c_v T_1} \frac{1}{\left[1 - \frac{1}{r}\right][\gamma - 1]} \quad (11)$$

3. In an air standard Otto cyle the pressure and temperature at the beginning of the cylcle is 42^0 C and 0.1MPa. The compression ratio and maximum temperature of the cycle are 8 and 1250^0 C respectively. Find (a) the temperature and pressure at the cardinal points of the cycle, (b) heat supplied per kg of air, (c) work done per kg of air (d) cycle efficiency and (e) the m.e.p. of the cylcle

Given data:

$p_1 = 0.1MPa = 100 kN/m^2$

$T_1 = 42^0C = 315K$

$r = 8$

$$r = 8\left(i.e \frac{V_1}{V_2} = \frac{V_4}{V_3} = 8 \right)$$

$T_3 = 1250^0C = 1523K$

solution

Consider process 1-2 (adiabatic process)

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

$$p_2 = \left(\frac{V_1}{V_2} \right) \times P_1 = (8)^{1.4} \times 100$$

$$P_2 = 1837.9 kN/m^2$$

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

$$T_2 = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \times T_1 = (8)^{1.4-1} \times 315$$

$$T_2 = \mathbf{723.68K}$$

consider process 2-3 (constant volume process);

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

$$p_3 = \frac{T_3}{T_2} \times p_2 = \frac{1523}{723.68} \times 1837.9$$

$$p_3 = \mathbf{3867.89kN/m^2}$$

Consider process 3 - 4 (adiabatic process);

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

$$p_4 = \left(\frac{V_3}{V_4}\right) \times P_3 = \left(\frac{1}{8}\right)^{1.4} \times 3867.89$$

$$P_4 = \mathbf{210.44kN/m^2}$$

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

$$T4 = \left(\frac{V_3}{V_4}\right)^{\gamma-1} \times T_3 = \left(\frac{1}{8}\right)^{0.4} \times 1523$$

$$T_4 = \mathbf{662.9K}$$

Heat supplied, Q_s =$mC_v(T_3$-$T_2)$

=1 x 0.718 x (1523 – 723.68)

Q_s = 573.9 kJ/kg

Heat rejected Q_R= $mC_v(T_4$-$T_1)$ = 1 C0.718 X (662.9-315)

Q_R = 249.79 KJ/kg

Work done, W = Q_S – Q_R

W = 573.9 – 249.79

= 324.1 KjKG

Cycle efficiency,

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

$$= 1 - \frac{1}{(8)^{1.4-1}} = 0.5647$$

η = 56.47%

More effective pressure, p_m

$$p_1 v_1 = mRT_1$$

$$v_1 = \frac{mRT_1}{P_1} = \frac{1 \times 0.287 \times 315}{100}$$

v1 = 0.9m³/kg

$$\frac{v_1}{v_2} = 8 \Rightarrow v_2 = \frac{0.9}{9} = 0.11 m^3/kg$$

$$p_m = \frac{W}{v_1 - v_2} = \frac{324.1}{0.9 - 0.11}$$

p_m = 409.2 kN/m²

Alternatively, we can use mean effective pressure formula,

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

$$k = \frac{p_3}{p_2} = \frac{3867.89}{1837.9} = 2.10$$

$$p_m = 100 \times 8 \times \left(\frac{2.1-1}{1.4-1}\right)\left(\frac{8^{1.4-1}-1}{8-1}\right)$$

p_m = 407.75 Kn/m²

4. Air enters in an air standard Otto cycle at 1bar and 290k. The ratio of heat rejection and heat supplied is 0.4. The maximum Temperature of the cycle is 1500k. Find efficiency, compression ratio, and network and mean effective pressure.

Given data:

$p_1 = 1$ ***bar***

$T_1 = 290K$

$$\frac{Q_R}{Q_S} = 0.4$$

$T_3 = 1500K$

Solution:

Efficiency of the cycle,

$$\eta = 1 - \frac{Q_R}{Q_S}$$

$= 1 - 0.4$

$\eta = 60\%$ Ans.

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

$$0.6 = 1 - \frac{1}{(r)^{1.4-1}} \Rightarrow r = \left(\frac{1}{0.4}\right)^{\frac{1}{0.4}}$$

$r = 9.88$ Ans.

Compression ratio, r = 9.88

$$v_1 = \frac{RT_1}{p_1} = \frac{287 \times 290}{1 \times 10^5}$$

$v_1 = 0.8323\ m^3/kg$

$$\frac{v_1}{v_2} = 9.88$$

$$v_2 = \frac{0.8323}{9.88} = 0.0842 m^3/kg$$

$$T_2 = T_1 \times (r)^{\gamma-1}$$

$$= 290 \times (9.88)^{1.4-1} = 725K$$

Heat supply, $Q_s = C_v (T_3 - T_2)$

$= 0.718 \times (1500 - 725)$

$= 556.45$ *kJ/kg*

Work done, $W = \eta \times Q_s = 0.6 \times 556.45$

= 333.87 *kJ/kg* **Ans.**

Mean effective pressure, *p_m*

$$p_m = \frac{W}{v_1 - v_2} = \frac{333.87}{0.8323 - 0.0842}$$

Pm = 446.29kN/m² ***Ans.***

5 **A six cylinder petrol engine has a compression ratio of 5:1. The clearance volume of each cylinder is 110CC. It operator on the four stroke constant volume cycle and the indicated efficiency ratio referred to air standard efficiency is 0.56. At the speed of 2400 rpm. It consumer 10kg of fuel per hour. The calorific value of fuel is 44000KJ/kg. Determine the average indicated mean effective pressure.**

Given data:

r = 5

V_C=110CC

$\eta_{relative}$ = 0.56

N = 2400rpm

M_f = 10kg

= 10/3600 kg/s

C_v = 44000kJ/kg

Z = 6

Solution:

Compression ratio:

r = $V_s + V_c/V_c \rightarrow 5 = V_s + 110/110 \rightarrow V_s = 440CC = 44x10^{-6}m^3$

Air standard efficiency:

$\eta = 1- 1 / (r^{\gamma-1}) = 47.47\%$ $(\gamma = 1.4)$

Relative efficiency:

$\eta_{relative} = \eta_{actual} / \eta_{air-standard} \rightarrow$

$0.56 = \eta_{actual}/47.47$ η_{actual}

= 26.58%

Actual efficiency = work output/ head input

$0.2658 = W/ m_f C_V \rightarrow W = 0.2658$

x 10/3600x44000 W =

32.49kw.

The network output:

$W= P_m \times V_s \times N/60 \times Z \rightarrow 32.49\times10^3 = Pm \times 440 \times10^{-6} \times$

1200/60 x 6

Pm = 6.15 bar

6. The efficiency of an Otto cycle is 60 % and γ = 1.5, what is the compression ratio?

Given:

Cycle efficiency (η) = 0. 6

γ = 1. 5

Required: r

Solution:

Compression ratio (r) = V_1 / V_2

We know that, $\eta = 1 - 1/r^{\gamma - 1}$

$0.6 = 1 - 1/ r^{1.5 - 1}$

r = 6.25 --- Ans

7. An engine of 250 mm bore and 375 mm stroke works on Otto cycle. The clearancevolume is 0.00263 m^3. The initial pressure and temperature are 1 bar and 50°C. If the maximum pressure is limited to 25 bar, find (i) air standard efficiency of the cycle (ii) the mean effective pressure of the cycle.

Given:

Bore (d) = 0.25 m

Stroke (L) = 0.375 m

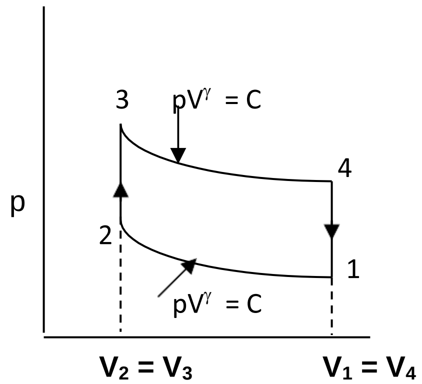
Clearance volume (V_2) = 0.00263

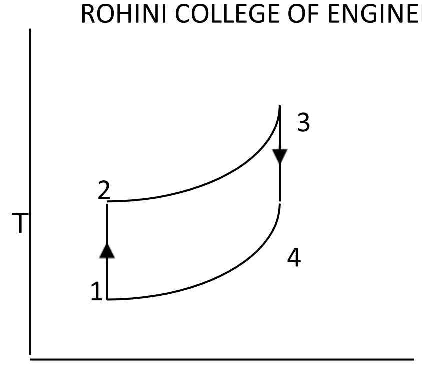
m^3Initial pressure (p_1) = 1 bar

Initial temperature (T_1) = 50°C = 323 K

Maximum pressure (p_3) = 25 bar

***Required:* (i) η (ii) p_m**





Solution:

(i) Cycle efficiency (η) = $1 - 1/r^{\gamma - 1}$

r = compression ratio = V_1 / V_2

V_1 = stroke volume + clearance volume

$= (V_1 - V_2) + V_2$

$= (\pi/4)\, D^2 L + V_2$

$= (\pi/4) \times 0.25^2 + 0.375 + 0.00263$

$= 0.021038\ m^3$

$\therefore$ r = 0. 021038 / 0. 00263 = 8

$\therefore$ $\eta = 1 - 1/8^{1.4-1} = 0.565$ --- Ans

(ii) Mean effective pressure (p_m)

$$Pm = p_1\, r \left[\frac{(r^{\gamma - 1} - 1)(r_p - 1)}{(\gamma - 1)(r - 1)}\right]$$

→ for Otto cycle

$r_p = p_3 / p_2$

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

$p_2 = (V_1 / V_2)^{\gamma}\ p_1 = (8)^{1.4} \times 1 = 18.38$ bar

$\therefore$ r_p = 25/18. 38 = 1.36

$$p_m = 1 \times 8 \left[\frac{(8^{1.4-1} - 1)(1.36 - 1)}{(1.4 - 1)(8 - 1)}\right]$$

p_m = 1.334 bar Ans

8 Air enters an air standard Otto cycles at 100 kN/m^2 and 290 K. The ratio of heat rejection to heat

supplied is 0.4. The maximum temperature in the cycle is 1500 K.Find (a) efficiency, (b) network, (c) mep, & (d) compression ratio (r).

Given:

Initial pressure (p_1) = 100 kN/m^2 = 1

barInitial temperature (T_1) = 290 K

Heat rejection / Heat supplied = 0.4

Maximum temperature (T_3) = 1500 K

Required: **(a) η (b) W_{net} (c) mep (d)**

r*Solution:*

(a) Cycle efficiency (η) = $1 - 1 / r^{\gamma - 1}$

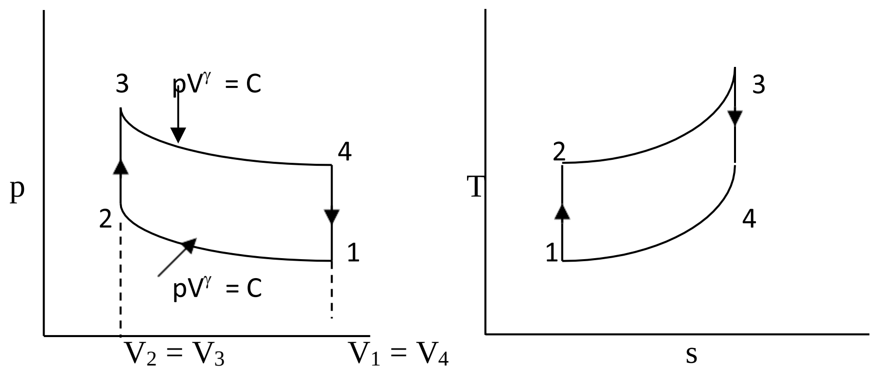
= (heat supplied – heat rejection) / heat supplied

= 1 – (HR / HS) = 1 – 0.4 = 0.6---- Ans

(b) Network (W_{net}) = Heat supplied – Heat rejected

Heat supplied = m C_v ($T_3 - T_2$)

Take m = 1 kg & C_v = 0.717 kJ/kgK



<u>To find T_2</u>

$$T_2 / T_1 = (p_2 / p_1)^{(\gamma - 1)/\gamma} = (V_1 / V_2)^{(\gamma - 1)}$$

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

From , $\eta = 1 - (1/ r^{\gamma - 1})$

i.e., $0.6 = 1 - (1 / r^{1.4-1})$

r = 9.88

$\therefore$ **$T_2 = 290\ (9.88)^{1.4-1} = 725$ K**

$\therefore$ **Heat supplied = 1 x 0.717 x (1500 – 725) = 555.675 kJ**

Heat rejected = 0.4 (555.675) = 222.27 kJ

$\therefore$ **W_{net} = 555.675 – 222.27 = 333.405 kJ---- Ans**

(c) MEP

$$p_m = p_1\ r \left[\frac{(r^{\gamma-1} - 1)(r_p - 1)}{(\gamma - 1)(r - 1)}\right] \rightarrow \text{for Otto cycle}$$

$r_p = p_3 / p_2$

2– 3 → Constant volume process

$p_3 / T_3 = p_2 / T_2$

$\therefore p_3 / p_2 = T_3 /$

T_2 **<u>To find T_2</u>**

$T_2 / T_1 = (V_1 / V_2)^{\gamma-1}$

$T_2 = 290\ (9.88)^{1.4-1} = 724.94$ K

$Rp = p_3 / p_2 = 1500 / 724.94 = 2.069$

$$p_m = 1 \times 9.88 \left[\frac{(9.88^{1.4-1} - 1)(2.069 - 1)}{(1.4 - 1)(9.88 - 1)}\right]$$

= 4.459 bar-------Ans