A TEXTBOOK OF THERMAL ENGINEERING

[SI UNITS]

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Chapter-1 :- performance of an I.C engine :-

performance is based upon testing & in this case.

purpose of testing are,

→ To avail or to get the information which can't be obtain by calculation.

→ To satisfy the customer regarding the performance of the engine.

→ Testing is done in order to determine the following quantities.

a. Indicated mean effective pressure

b. Indicated power

c. Speed of the engine

d. Break torque

e. Break power

f. Mechanical losses

g. efficiencies

h. air consumption.

i. Indicated diagram :-

It is a chart or graphical representation of the variation in pressure & volume of steam inside the cylinder or pv diagram.

j. Indicated mean effective pressure :-

(i) The average pressure produced in the combustion chamber during the operating cycle.

(ii) It is a quantity related to the operation of a reciprocating engine & is a malleable measure of engine capacity to do work.

(iii) It is obtain from the indicated diagram.

K. Indicated power :-

The indicated power (IP) is the power actually developed by the engine cylinder. It is based on the information obtain from the indicated diagram of the engine.

P_m = mean effective pressure

L = Length of the stroke

A = Area of the piston

N = speed of the engine

K = number of cylinder

n = number of working stroke/minute.

For 2-stroke → n = N

For 4-stroke → n = N/2

~~IP = (Pm x 10^5) x LANK~~

$IP = (P_m \times 10^5) \times L \times A \times n \times K$ J/minute

$IP = \frac{(P_m \times 10^5) \times LAnK}{60}$ watt

$IP = \frac{(P_m \times 100) \times LAnK}{60}$ kwatt

$IP = \frac{P_m \times LAnK}{60}$ watt

if P_m is in P_a.

Question :-

1) A two stroke gas engine has piston diameter of 150 mm; length of stroke = 400 mm, P_m = 5.5 bar. The makes 120 explosions per minute, Determine the IP.

Given data,

diameter of the piston (d) = 150mm = 150×10^{-3} m

Length of stroke (L) = 400mm = 400×10^{-3}

P_m = 5.5 bar

N = 120 rpm

Area of cylinder = $\frac{\pi}{4} \times (150 \times 10^{-3})^2$ = 0.0176

$IP = \frac{(P_m \times 10^5) \times LAN}{60}$

$= \frac{(5.5 \times 10^5) \times 0.4 \times 0.0176 \times 120}{60}$

= 7775.44 watt

= 7.77 KW.

2) A four cylinder two stroke cycle petrol engine runs at 2500 rpm. The P_m on each piston is 8.5 bar, the diameter of each cylinder is 150 mm. Calculate the IP if length of stroke is 2.4 times of it's radius

Given data,

K = 4

N = 2500 rpm

P_m = 8.5 bar

d = 150 mm = 0.15 m

$L = 2.4 \times r = 2.4 \times \frac{0.15}{2} = 0.18$ m

Area = $\frac{\pi}{4} \times d^2 = \frac{\pi}{4} \times 0.15^2 = 0.01767$

$\Rightarrow IP = \frac{8.5 \times 10^5 \times .18 \times 0.01767 \times 2500 \times 4}{60} = 450622.19$ watt

= 450.6 KW

★ Morse test :-

Morse test is adopted to find the IP of a high speed IC engine without using indicated diagram.

→ Considering a four cylinder engine, first of all break power of the engine is calculated when all cylinder are in operations at a constant speed & load.

→ Now one of the cylinder is cut off, so that it doesn't develope any power.

→ This is done by short circuiting the spark plug of the cylinder in petrol engine & cutting of individual fuel supply in diesel engine.

→ The Speed of the engine decreases & in order to bring Speed back to its original Speed the load on the engine is reduced.

→ The break power is now measured in this new condition.

→ Similarly each cylinder is cutoff one by one & break power of remaining cylinder is calculated.

let I_1, I_2, I_3, I_4 equal to IP of each cylinder.

let F_1, F_2, F_3, F_4 equal to frictional power (F_p) of each cylinder.

Total break power of the engine when all cylinder are acting.

$B.P = I.P - F.P$

$\Rightarrow B = (I_1 + I_2 + I_3 + I_4) - (F_1 + F_2 + F_3 + F_4)$ —(I)

when cylinder one is cut off, $I_1 = 0$ but F_p remains same.

B.P. of remaining cylinder,

$B_1 = (0 + I_2 + I_3 + I_4) - (F_1 + F_2 + F_3 + F_4)$ —(II)

Subtracting eqn-(II) from eqn-(I) we get,

$B - B_1 = I_1$

∴ IP of cylinder, $I_1 = B - B_1$

Similarly, IP of other cylinder,

$I_2 = B - B_2$

$I_3 = B - B_3$

$I_4 = B - B_4$

total $I_P = I_1 + I_2 + I_3 + I_4$

Exercises :-

2) A two stroke cycle IC engine has a Pm of 6 bar. The speed of the engine is 1000 rpm. If the diameter of piston & stroke are 110 mm & 140 mm respectively, find the IP.

Given data,

$P_m = 6$ bar

$N = 1000$ rpm

$d = 110$ mm $= 0.11$ m

Area $= \frac{\pi}{4} d^2 = 9.50 \times 10^{-3}$

& $L = 140$ mm $= 0.14$ m

$$I_P = \frac{6 \times 10^5 \times 0.14 \times 9.50 \times 10^{-3} \times 1000}{60}$$

$= 13300$ W

$= 13.3$ kW.

3) A gas engine has a piston diameter of 150 mm & stroke 250 mm. The speed of the engine is 250 rpm & the average number of explosions are 90 per minute. The Pm is 7 bar. If the average torque on the brake is 140 N-m, find the IP, ~~break~~ brake power & mechanical efficiency.

$d = 150$ mm $= 0.15$ m

$L = 250$ mm $= 0.25$ m

$N = 250$ rpm

$n = 90$

$A = \frac{\pi}{4} \times 0.15^2 = 0.01767$

$P_m = 7$ bar

$$I_P = \frac{P_m \times LAN}{60} = \frac{7 \times 10^5 \times 0.25 \times 0.01767 \times ~~250~~ 90}{60}$$

~~= 12884.3 W~~ $=$ ~~468~~ 4638.3 W

~~= 12.88 kW~~ $= 4.63$ kW

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→ Indicated mean effective pressure using indicator diagram:

$$P_m \text{ (bar)} = \frac{\text{Area of indicator diagram (mm}^2)}{\text{Length of indicator diagram (mm)}} \times \text{(Scale of indicator spring) (spring number) (bar/mm)}$$

$$P_m = \frac{a \times S}{L}$$

Brake power :-

→ Brake power is defined as the power developed by engine at the output shaft. or power developed or available at the crankshaft.

→ Brake, in the name, refers to (Brake dynamometer) as it helps in measuring power available in output (O/p-engine, i/p - compressor).

→ Brake power of an IC engine can be measured by means of brake mechanism (prony brake or rope brake)

In case of prony brake,

$$\text{Brake power} = \frac{\text{Torque (N-m)} \times \text{Angle turned in radians through 1 rev?}}{60}$$

$$B.P = \frac{T \times 2\pi N}{60} \quad \text{or} \quad B.P = T \times \omega \text{ (omega)}$$

$T = W \times L$; W = Brake load (Newton)
L = Length of arm (m)
N = speed of engine (rpm)
T = Torque (N-m)

In case of rope brake,

$$\text{Brake power} = \frac{(W-S)\pi DN}{60} \quad \text{(when 'd' isn't considered)}$$

$$B.P = \frac{(W-S)\pi (D+d)N}{60} \quad \text{(when } \phi \text{ is considered)}$$

W = Dead load (N)
S = spring balance reading (N)
D = Diameter of brake drum (m)
d = diameter of rope (m)
N = speed of engine (rpm)

Question :-

1) A single cylinder two stroke petrol engine develops 4 kW IP. Find the average speed of the piston if P_m is 6.5 bar & piston diameter is 100 mm.

Average speed of a piston is a function of stroke & engine speed }
& it is given by $N_p = 2 \times L \times N$

Given data, $IP = 4\ kW$
$P_m = 6.5$ bar
$d = 100mm = 0.1m$, $A = \frac{\pi}{4} \times 0.1^2 = 7.85 \times 10^{-3}\ m^2$

$$IP = \frac{P_m \times LAN}{60}$$

$$\Rightarrow L \times N = \frac{IP \times 60}{P_m \times A} = \frac{4 \times 10^3 \times 60}{6.5 \times 10^5 \times 7.85 \times 10^{-3}}$$

$\Rightarrow LN = 47\ m/s$

∴ average speed of the piston $(N_p) = 2 \times LN$
$= 2 \times 47$
$= 94\ m/s$

2) In a laboratory experiment following observations are noted for a four stroke diesel engine.

i) Area of indicator diagram = 420 mm²
ii) length " " " = 62 mm
iii) Spring number = 1.1 bar/mm
iv) Diam. of piston = 100 mm
v) length of stroke = 150 mm
vi) Engine speed (N) = 450 rpm

Determine
a. Indicated mean effective pressure.
b. I.P.

Given data, 'A' of indicator diagram = 420 mm²

L of " " = 62 mm

S = 1.1 bar/mm

D = 100 mm

L = 150 mm

N = 450 rpm

for a four stroke engine, $n = N/2$

$P_m = \frac{A \times S}{L} = \frac{420 \times 1.1}{62} = 7.45$ bar

$IP = \frac{P_m \times LAN/2}{60}$ $\quad A = \frac{\pi}{4} \times 0.1^2 = 7.85 \times 10^{-3}$

$= \frac{7.45 \times 10^5 \times 0.150 \times 7.85 \times 10^{-3} \times 450/2}{60}$

$= 3289.64$ W

$= 3.28$ KW

Efficiencies :-

Efficiency of I.C engines is defined as the ratio of workdone to the energy supplied.

1) Mechanical efficiency :- (η_{mech})

It is the ratio of Brake power to the indicated power.

$\eta_{mech} = \frac{B.P}{I.P}$

Since, B.P. is less than IP due to frictional losses (FP), η_{mech} is always less than 1.

$\eta_{mech} < 1$
& F.P = I.P − B.P

2) Overall efficiency :- (η_o)

It is the ratio of work obtained at the crank shaft in a given time to the energy supplied by fuel during the same time.

Calorific value of fuel/Heat value :-

Calorific value of solid or liquid fuel can be defined as amount of heat given out by the complete combustion of 1 kg of fuel.

It is expressed in KJ/kg of fuel

Let m_f = mass of fuel consumed in kg/hour

C = Calorific value of fuel

Now, heat supplied by fuel per minute, $= \frac{m_f \times C_V}{60}$ KJ

B.P. (power) available at crankshaft per minute = BP × 60 KJ

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$$\eta_0 = \frac{Bp \times 60}{\frac{m_f \times CV}{60}} = \frac{3600\,Bp}{m_f \times C_v}$$

$$\boxed{\eta_0 = \frac{3600\,Bp}{m_f \times CV}}$$

Bp in kW
m_f in kg/hr
CV in kJ/kg of fuel.

3) ~~A gas Engine has~~

Q.1). Gas engine, $L = 400\,mm$
$D = 150\,mm$
$P_m = 5.5\,bar$
120 explosions/minute
Find η_{mech} if $BP = 5\,kW$.

$IP = 7.77\,kW$

$$\eta_{mech} = \frac{BP}{IP} = 0.6435$$
$= 64.35\%$

H.W.
Pg.633) 1, 3, 4, 7, 12

indicated thermal efficiency $= \frac{3600\,IP}{m_f \times C_v}$

Exercises:-

1) The following data were recorded during testing of a four stroke cycle gas engine:
Area of indicator diagram = 900 mm²; Length of indicator diagram = 70 mm; spring scale = 0.3 bar/mm; Length of stroke = 250 mm; speed = 300 rpm Determine:
I. ~~IP~~ Indicated mean effective pressure (P_m)
II. IP

Given data, ~~A = 900 mm²~~
Area of indicator diagram = 900 mm²
Length " " " = 70 mm

4) During a trial of a single cylinder four stroke I.C. engine, the following observations are recorded:

$P_m = 4$ bar ; Speed = 2000 rpm ; BP = 7.5 kW ; L = 1.5 times diameter of piston. If the η_{me} is 70%. Find the dimensions of the engine.

Given data, $P_m = 4$ bar

$N = 200$ rpm

$BP = 7.5$ kW

$L = 1.5d$

$\eta_{me} = 70\% = 0.7$

for four stroke cycle engine, $n = N/2$

$\eta_{mech} = \frac{BP}{IP}$

$\Rightarrow IP = \frac{BP}{\eta_{mech}} = \frac{7.5 \times 10^3}{0.7} = 10714.2$ W

$= 10.714$ kW

$IP = \frac{P_m \times LAN/2}{60}$

$10.714 \times 10^3 = \frac{4 \times 10^5 \times LXA \times 100}{60}$

$LXA = \frac{10.714 \times 10^3 \times 60}{4 \times 10^5 \times 100} = 0.016071$

$1.5 \times d \times \frac{\pi}{4} d^2 = 0.016071$

$d^3 = 0.016071 \times \frac{4}{\pi} \times \frac{1}{1.5}$

$= 0.013641$

$d = 0.2389$ m $= 239$ mm $\simeq 240$ mm

$L = 1.5 \times d = 0.3584 = 358.4$ mm $\simeq 360$ mm

7) Following observations were taken during the trial of a single cylinder, four stroke, oil engine, running at full load:

Area of indicator diagram = 300 mm²

length " " " = 40 mm

Spring stiffness = 1 bar/mm

Speed of engine (N) = 400 rpm

Brake load (W) = 400 N

Spring balance reading (S) = 50 N

diameter of brake drum = 1.2 m (D)

Fuel consumption per hour = 3 kg i.e. = 3 kg/hr.

CV = 42000 kJ/kg

Cylinder diameter (d) = 160 mm = 0.16 m

L = 200 mm = 0.2 m

Find the IP, BP, η_{me} & brake thermal efficiency.

Area of cylinder $= \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 0.16^2 = 0.02$

$n = N/2 = \frac{400}{2} = 200$ rpm

$P_m = \frac{\text{Area of indicator diagram}}{\text{length of indicator diagram}} \times \text{Spring stiffness}$

$= \frac{300}{40} \times 1$

$= 7.5$ bar

i. $IP = \frac{7.5 \times 10^5 \times 0.2 \times 0.02 \times 200}{60}$

$= 10,000$ W

$= 10$ kW

ii. $BP = \frac{(W-S) \times \pi D N}{60}$

$= \frac{(400 - 50) \times \pi \times 1.2 \times 400}{60}$

$= 8796.45$ W

$BP = 8.8$ kW

iii. $\eta_{me} = \frac{BP}{IP} = \frac{8.8}{10} = 0.88 = 88\%$

iv. Brake thermal efficiency $= \frac{3600 \times BP}{m_f \times C_V}$

$= \frac{3600 \times 8.8}{3 \times 42,000}$

$= 0.2514$

$= 25.14\%$

12) The following data relates to a four cylinder four stroke petrol engine :

$d = 80mm$

$L = 120\ mm$

Clearance volume $= 100 \times 10^3 mm^3$

Fuel supply(m_f) = 4.8 Kg/h

$C_V = 44100$ KJ/kg

Bp with all the cylinder working (B) = 14.5 KW

Bp with cylinder 1 cut-off = 9.8 KW (B_1)

Bp with cylinder 2 cutoff = ~~9.8~~ 10.3 KW (B_2)

Bp with cylinder 3 cut-off = 10.14 KW (B_3)

Bp with cylinder 4 cut off = 10KW (B_4)

Find IP of the engine & also calculate indicated thermal efficiency, brake thermal efficiency & relative efficiency.

1. Then, $I_1 = B - B_1 = 14.5 - 9.8 = 4.7$ KW

$I_2 = B - B_2 = 14.5 - 10.3 = 4.2$ KW

$I_3 = B - B_3 = 14.5 - 10.14 = 4.36$ KW

$I_4 = B - B_4 = 14.5 - 10 = 4.5$ KW

$I_P = I_1 + I_2 + I_3 + I_4 = 17.76$ KW

II. Indicated thermal efficiency $= \frac{3600 \times IP}{m_f \times C_V}$

$= \frac{3600 \times 17.76}{4.8 \times 44100}$

$= 0.302$

$= 30.2\%$

III. Brake thermal efficiency $= \frac{3600 \times BP}{m_f \times C_V}$

$= \frac{3600 \times 14.5}{4.8 \times 44100}$

$= 0.246$

$= 24.6\%$

8) The output of an I.C engine is measured by a rope brake dynamometer. The diameter of the brake pulley is 750 mm & rope diameter is 50 mm. The dead load on the right side of the rope is 410N and the spring balance reading is 50 N. The engine consumes 4kg/h of fuel at rated speed of 1000 r.p.m. The calorific value of fuel is 44100 KJ/kg. Calculate brake specific fuel consumption & the brake thermal efficiency.

Given data,

diameter of the brake pulley (D) = 750 mm = 0.75m

rope diameter (d) = 50 mm = 0.05m

dead load (W) = 410N

Spring balance reading (S) = 50N

m_f = 4 kg/h

N = 1000 rpm

C_V = 44100 KJ/kg

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11. Brake power (B.P) $= \frac{(W-S) \times \pi (D+d) N}{60}$

$= \frac{(410-50) \times \pi \times (0.75+0.05) \times 1000}{60}$

$= 15079.64$ W

$= 15$ KW

∴ Brake thermal efficiency $= \frac{3600 \times BP}{m_f \times CV}$

$= \frac{3600 \times 15}{4 \times 44100}$

$= 0.3061$

$= 30.61\%$

1. Brake Specific fuel Consumption $= \frac{m_f}{BP}$

$= \frac{4}{15} = 0.266$ Kg/BP/h

Question :-

4) A four cylinder two stroke cycle petrol engine have,

BP = 23.5 KW

N = 2500 rpm

P_m = 8.5 bar

η_{mech} = 85% = 0.85

L = 1.5 d

Find engine dimensions.

$\eta_{mech} = \frac{B.P}{I.P.}$

$I.P = \frac{B.P}{\eta_{mech}} = \frac{23.5}{0.85} = 27.64$ KW

$I_P = \frac{P_m LANK}{60}$

$L.A = \frac{I_P \times 60}{P_m \times NK} = \frac{27.64 \times 10^3 \times 60}{8.5 \times 10^5 \times 2500 \times 4}$

$1.5 d \times \frac{\pi}{4} d^2 = ~~7.80~~ 1.95 \times 10^{-4}$

$d^3 = 7.80 \times 10^{-4} \times \frac{4}{1.5\pi} = ~~6.62~~ 1.65 \times 10^{-4}$

~~d = 0.087 m = 87.18 mm~~

d = 0.0549 m = 55 mm

L = 1.5 × 55 mm = 82.37 mm

3) Indicated thermal efficiency (η_t) :-

It is the ratio of heat equivalent to one KW-hr to the heat in the fuel per I.P hour.

i.e. $\eta_t = \frac{3600}{\frac{m_f \times CV}{I.P}}$

→ $\eta_t = \frac{I.P \times 3600}{m_f \times C_v}$

Note :-

$\frac{m_f}{I.P}$ = Specific fuel consumption per I.P/hr.

$\frac{m_f}{B.P}$ = brake Specific fuel consumption per B.P/hr

4). Brake thermal efficiency (η_b) :-

It is the ratio of heat equivalent to 1kw hr to heat in fuel per B.P hr.

It is also known as Overall thermal efficiency.

Notes:-

$$\eta_b = 3600 \Big/ \frac{m_f \times CV}{BP}$$

$$\Rightarrow \eta_b = \frac{BP \times 3600}{m_f \times CV}$$

5) Air standard efficiency :- (η_{air})

It is defined as

$$\eta_{air} = 1 - \frac{1}{r^{\gamma-1}}$$ for petrol engine

$$\eta_{air} = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{r_c^{\gamma}-1}{\gamma(r_c-1)}\right]$$ for disel engine

6) Relative efficiency ($\eta_{Relative}$) :-

-> It is also known as efficiency ratio.

-> It is the ratio of indicated thermal efficiency to the air standard efficiency.

Mathematically, $\eta_R = \frac{\eta_t}{\eta_{air}}$

7) Volumetric efficiency (η_{vol}) :-

It is the ratio of actual volume of charge admitted during the suction stroke at N.T.P to the swept volume of the piston.

i.e. $\eta_{vol} = \frac{V_a}{V_s}$

where, V_a = volume of charge admitted

V_s = swept volume.

Question:-

5) Single cylinder, four stroke cycle engine have,

D_{brake} = 630 mm = 0.63 m

Dead load on brake (W) = 200 N

Spring balance reading (S) = 30N

Speed (N) = 450 rpm

Area of indicator diagram = 420 mm²

length of indicator diagram = 60mm

Spring scale = 1.1 bar/mm

D_c = 100 mm = 0.1 m

L_s = 150 mm = 0.15 m

Quantity of oil used (m_f) = 0.815 kg/h

Calorific value (CV) = 42000 J/kg

Find i) I.P.

ii) B.P

iii) η_{mech}

iv) η_b

v) Brake specific fuel consumption.

H/W

5, 6, 8, 11, 13

$P_m = \frac{420}{60} \times 1.1$

$= 7.7$ bar

Area of cylinder (A_c) = $\frac{\pi}{4} \times 0.1^2$

$= 7.85 \times 10^{-3}$ m^2

$n = N/2 = \frac{450}{2} = 225$

1. $I_P = \frac{P_m LAN/2}{60} = \frac{7.7 \times 10^5 \times 0.15 \times 7.85 \times 10^{-3} \times 225}{60}$

$= 3.4$ kW

11. $B.P = \frac{(200 - 30) \times \pi \times 0.63 \times 450}{60} = 2.52$ kW

111. $\eta_{mech} = \frac{IP}{BP} = 0.7411 = 74.11\%$

IV. $\eta_b = \frac{BP \times 3600}{m_f \times CV} = \frac{2.52 \times 10^3 \times 3600}{0.815 \times 42000}$

$= 0.265$

$= 26.5\%$

v. brake specific fuel consumption $= \frac{m_f}{B.P} = \frac{0.815}{2.52} = 0.323$ kg/BP/hr

6) A four cylinder engine running at 1200rpm gave 18.6 kW BP. The average torque when one cylinder was cutout was 105N-m. Determine the indicated thermal efficiency if CV of the fuel is 42,000 KJ/kg & engine uses 0.34kg of petrol per brake power hour.

Given data, N=1200 rpm

BP = 18.6 kW (for 4 cylinder)

$T_{avg-3} = 105$ N-m

$\eta_t = ?$

CV = 42,000 kJ/kg

$m_f = 0.314 \frac{kg}{BP \times hr}$

for three

$BP = \frac{T \times 2\pi N}{60} = \frac{105 \times 2 \times \pi \times 1200}{60}$

$= 13.19$ kW ≈ 13.2 kW

$IP_1 = BP - BP_1$

$= 18.6 - 13.2 = 5.4$ kW

~~$IP_1 = B - B_1 = 18.6 - 13.19$~~

$IP = 5.4 \times 4 = 21.6$

for four cylinder, BP = 18.6 kW

" one ", BP = 4.65 kW

" three ", BP = 4.65×3 = 13.95 kW

∴ $F.P_{one\ cylin} = 13.95 - 13.19 = 0.76$ kW

for four cylinder, FP = $0.76 \times 4 = 3.04$ kW

~~IP = BP+FP = 13.9 18.6×10³ +1.01~~

~~= 19.61~~

IP = BP+FP = 18.6+3.04 = 21.64 kW

$\eta_t = \frac{3600\ IP}{m_f \times CV}$

given $m_f = 0.34 \frac{kg}{BP \times hr}$.

it means, $\frac{m_f}{BP} = 0.34$ kg/BP/hr

$m_f = 0.34 \times 18.6 = 6.324$ kg/hr.

$\eta_t = \frac{3600\ IP}{m_f \times CV} = \frac{3600 \times 21.64}{6.324 \times 42000} = 0.2933$

$= 29.33\%$

5. A constant speed four stroke cycle compression ignition engine has a bore of 100 mm, stroke 150mm & runs at 450 rpm. The following data refer to a test on this engine.

Brake wheel diameter = 600mm; Band thickness = 5mm; Load on band = 210N; spring balance reading = 30N; Area of indicator diagram = 415 mm²; length of indicator diagram = 62.5 mm; Spring scale = 1.1 bar per mm; Specific fuel consumption = 0.3kg/bp/h; calorific value of fuel = 42000 kJ/kg

Calculate: 1 the mechanical efficiency & 2 the indicated thermal efficiency.

Given data, $d = 100mm = 0.1m$

$L = 150mm = 0.15m$

$N = 450 rpm$, $n = N/2 = 225$

Brake wheel diameter $(D) = 600mm = 0.6$

$d = 5mm = 0.005$

$W = 210N$

$S = 30N$

Area of indicator diagram = 415mm²

length " " " = 62.5mm

Spring scale = 1.1 bar/mm

$\frac{m_f}{BP} = 0.3$ kg/bp/h $\Rightarrow m_f = 0.3 \times BP$

$CV = 42000$ kJ/kg

$A = \frac{\pi}{4} \times 0.1^2 = 7.85 \times 10^{-3} m^2$

$P_m = \frac{415}{62.5} \times 1.1 = 7.304$ bar

$IP = \frac{P_m LAN}{60} = \frac{7.304 \times 10^5 \times 0.15 \times 7.85 \times 10^{-3} \times 225}{60}$

$= 3.22$ kW

$BP = \frac{(210-30) \times \pi \times (0.6+0.005) \times 450}{60}$

$= 2.56$ kW

1. $\eta_{mech} = \frac{BP}{IP} = \frac{2.56}{3.22} = 0.795$

$= 79.5\%$

II. $\eta_{t} = \frac{3600 \times IP}{m_f \times CV} = \frac{3600 \times 3.22}{0.3 \times 2.56 \times 42000} = 0.3593$

$= 35.93\%$

6. The following data refer to test on a petrol engine:

$IP = 30$ kW

$BP = 26$ kW

$N = 1800$ rpm

$\frac{m_f}{BP} = 0.35$ kg/kW/hr

$CV = 42100$ kJ/kg.

Calculate: 1. η_{mech}, II. η_t & 3. η_b.

1. $\eta_{mech} = \frac{26}{30} = 0.8666$

$= 86.66\%$

$\frac{m_f}{BP} = 0.35$

$m_f = 0.35 \times BP$

II. $\eta_t = \frac{3600 \times IP}{m_f \times CV} = \frac{3600 \times 30}{26 \times 0.35 \times 42100} = 0.2819 = 28.19\%$

III. $\eta_b = \frac{3600\ BP}{m_f \times CV} = \frac{3600 \times 26}{26 \times 0.35 \times 42100} = 0.2443$

$= 24.43\%$

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11. An engine is used on a Job requiring 110 KW BP, the mechanical efficiency of the engine is 80% & the engine uses 50 kg fuel per hour under the conditions of operation. A design improvement is made which reduces the engine friction by 5 kW. Assuming the indicated thermal efficiency remains the same, how many kg of fuel per hour will be saved.

Given data, BP = 110 KW (require)

$\eta_{mech} = 80\% = 0.8$

$m_f = 50\ Kg/hr$

$IP = \frac{110}{0.8} = 137.5\ KW$

$FP = 137.5 - 110 = 27.5\ KW$

As we require 110 KW BP & engine friction is reduced by 5 KW so that IP reduces to 5 KW

so final IP = 137.5 − 5 = 132.5

According to the question final & initial indicated thermal efficiency remains same, so that

$\Rightarrow \frac{3600\ IP}{m_f^* \cdot CV} = \frac{3600\ IP}{m_f \cdot CV}$

$\Rightarrow \frac{132.5}{m_f^*} = \frac{137.5}{50}$

$\Rightarrow \frac{132.5}{137.5} \times 50 = m_f^*$

$\Rightarrow m_f^* = 48.18$

∴ Quantity of fuel saved ; $m_f - m_f^* = 50 - 48.18$

$= 1.81\ Kg/h$

13. A petrol engine uses per brake power hour 0.36 kg of fuel of calorific value 44100 KJ/kg. The η_{mech} is 78%, & compression ratio 5.6. Calculate 1. η_b 2. η_t 3. Ideal air standard efficiency. Take r = 1.4.

Given data, $\frac{m_f}{BP} = 0.36\ Kg/bp/hr.$

$CV = 44100\ KJ/kg$

$\eta_{mech} = 78\% = 0.78$

$\frac{V_3}{V_4} = 5.6 = (r_c)$

given, $\frac{m_f}{bp} = 0.36$ $\qquad \frac{BP}{IP} = 0.78$

$m_f = 0.36 \times bp$ $\qquad \frac{BP}{0.78} = IP \quad —(1)$

1. then, $\eta_b = \frac{3600\ bp}{m_f \times CV} = \frac{3600\ bp}{0.36 \times bp \times 44100}$

$= 0.2267$

$= 22.67\%$

III. $\eta_{air} = 1 - \frac{1}{r_c^{r-1}} = 1 - \frac{1}{5.6^{1.4-1}}$

$= 0.498$

$= 49.8\%$

II. $\eta_t = \frac{3600\ IP}{m_f \times CV}$

Put the value of eqn (1) in this eqn we get

$= \frac{3600 \times BP/0.78}{m_f \times CV}$

$= \frac{3600}{\frac{m_f}{BP} \times CV \times 0.78} = \frac{3600}{0.36 \times 44100 \times 0.78}$ $\quad (\frac{m_f}{bp} = 0.36)$

$= 0.29$

$= 29\%$

~~9. Bp = 7.5 kW~~ Air fuel ratio :- (A/F)

F.P = 1.5 kW → It is defined as the mass ratio of air to solid, liquid or gaseous fuel present in a pre-combustion process.

$\eta_t = 0.42$

→ It determines whether a mixture is combustible or ~~not~~ all.

→ It is an important measure for anti pollution & performance - tunning ~~pose~~ reasons.

→ It exactly enough air is provided to completly burn all of the fuel, the ratio is known as stoichiometric mixture.

$$\boxed{A/F = \frac{m_a}{m_f}}$$

Ratio lower than ~~AFR~~ AFR_{stoich} = Rich mixture

Ratio higher than AFR_{stoich} = Lean mixture
(for comb^n 1 s fuel → min 15 g air) 1:15

Fuel air ratio :-

$$FAR = \frac{1}{AFR} \qquad \boxed{F/R = \frac{m_f}{m_a}}$$

It is used in gas turbine industries.

~~to~~ Air fuel equivalent ratio (λ) :- $\lambda = \frac{Act - AFR}{Stoch \cdot AFR}$

It is the ratio of actual AFR to stoichometric AFR.

9. BP = 7.5 kW $\quad \eta_t = 0.42$

FP = 1.5 kW $\quad A/F = 22$

IP = 9 kW $\quad CV = 43,260$ kJ/kg

i. $m_f = \frac{3600 \times 9}{0.42 \times 43260} = 1.783$ kg/h

ii. $\frac{m_a}{m_f} = 22 \Rightarrow m_a = 22 \times 1.783 = 39.23$ kg/h

iii. $\eta_b = \frac{3600 \times 7.5}{1.783 \times 43,260} = 35\%$

Chapter (10/4/18, 14) :- Reciprocating Air Compressor :-

~~It is a~~

→ Air compressor is a machine used to compress the air & to raise it's pressure.

→ It sucks air from the atmosphere, compresses it & then delivers the same under a high pressure to a storage vessel.

Application :-

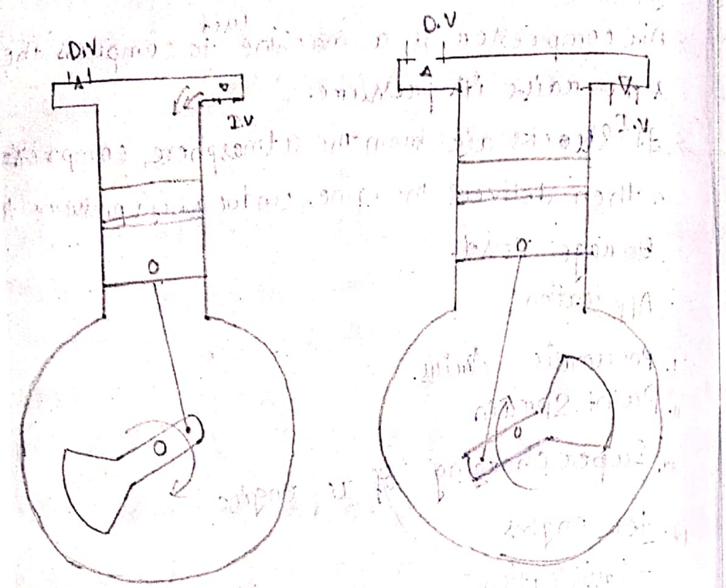
i. Pneumatic drills.
ii. Paint sprain
iii. Super charging of IC engine
iv. jet engines

Classification :-

1. According to working
   (i) reciprocating compressors
   (ii) Rotary compressors.
2. According to action.
   (i) Single acting compressor
   (ii) double acting compressor
3. No. of stages
   (i) Single stage compressor.
   (ii) Multi stage compressor.

~~Com~~

Working of single stage reciprocating air compressor



→ It consists of a cylinder, piston, inlet & discharge valve.

→ when piston moves downward the pressure inside the cylinder falls below the atmospheric pressure.

→ due to this pressure difference the inlet valve gets opened and air is sucked into the cylinder at the inlet pressure. This stroke is known as suction stroke.

→ Now when piston moves upward pressure inside the cylinder increases till it reaches discharge pressure

→ At this stage discharge valve gets opened and compressed air is delivered.

→ at the end of the stroke a small quantity of air gets trapped in the clearance volume. Now as the piston starts it's suction stroke the trapped air expands till it reaches atm. pressure (Patm).

→ At this stage, inlet valve gets opened & the cycle is repeated.

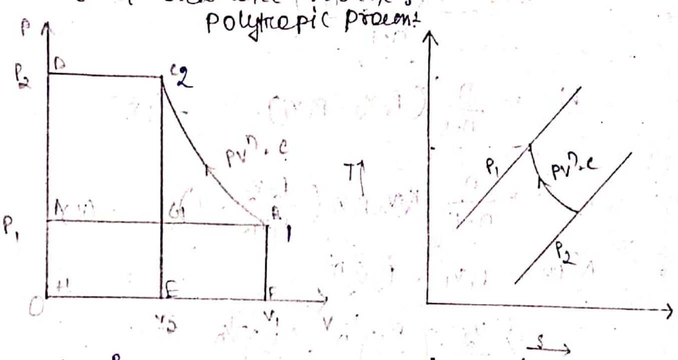
Here, suction, compression & delivery of air takes place in two strokes of the piston or one revolution of the crankshaft.

~~Single stage reciprocati~~

W.D by a single stage reciprocating air compressor :–

1. Without clearance volume :–

Polytropic process



Considering a single stage reciprocating air compressor delivering air,

m = mass of air sucked by piston per cycle.

P_1 = Inlet pressure or pres. of air before comp.

V_1 = Initial volume of air

P_2 = Discharge pressure or pres. of air after comp.

V_2 = Final volume of air

Pressure ratio, $(r) = \frac{P_2}{P_1}$

W.D by a compressor per cycle = W.D on area ABCD

= W.D on area BCEH + W.D on area BCEF − W.D on area ABFH

W.D by a compressor per cycle = Area ABCD

= Area HECD + Area BFEC − Area ABFH

$= P_2V_2 + \frac{P_2V_2 - P_1V_1}{n-1} - P_1V_1$

($PV^n = C$: $P_1V_1^n = P_2V_2^n$, $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$, $\left(\frac{P_2}{P_1}\right)^{1/n} = \left(\frac{V_1}{V_2}\right)$, $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$, $\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n$)

$$= \frac{(n-1) P_2 V_2 + P_2 V_2 - P_1 V_1 - (n-1) P_1 V_1}{n-1}$$

$$= \frac{(n P_2 V_2 - P_2 V_2) + P_2 V_2 - P_1 V_1 - (n P_1 V_1 - P_1 V_1)}{n-1}$$

$$= \frac{n P_2 V_2 - n P_1 V_1}{n-1}$$

$$W = \frac{n}{n-1} (P_2 V_2 - P_1 V_1) \quad -(I)$$

$$= \frac{n}{n-1} P_1 V_1 \left(\frac{P_2 V_2}{P_1 V_1} - 1 \right) \quad -(II)$$

Now, $P_1 V_1^n = P_2 V_2^n$

$$\Rightarrow \frac{V_2}{V_1} = \left(\frac{P_1}{P_2} \right)^{1/n} = \left(\frac{P_2}{P_1} \right)^{-1/n}$$

Using the above relation

$$W = \frac{n}{n-1} P_1 V_1 \left[\frac{P_2}{P_1} \left(\frac{P_1}{P_2} \right)^{1/n} - 1 \right]$$

$$= \frac{n}{n-1} P_1 V_1 \left[\frac{P_2}{P_1} \times \left(\frac{P_2}{P_1} \right)^{-1/n} - 1 \right]$$

$$= \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{1-1/n} - 1 \right]$$

$$= \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad -(III)$$

$$= \frac{n}{n-1} P_1 V_1 \left[\frac{T_2}{T_1} - 1 \right] \qquad \left(\because \frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right)$$

$$= \frac{n}{n-1} m R T_1 \left[\frac{T_2}{T_1} - 1 \right]$$

$$= \frac{n}{n-1} m R T_1 \frac{(T_2 - T_1)}{T_1}$$

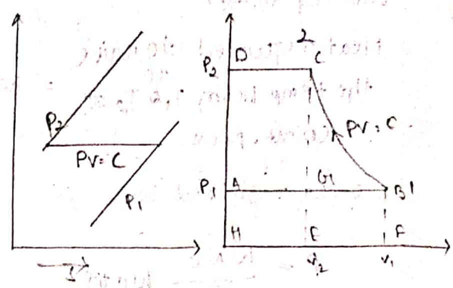
$$= \frac{n}{n-1} m R (T_2 - T_1)$$

Isentropic & adiabatic / adiabatic isentropic

(5b) (i)

Isothermal :-

W.D during



W.D during compression per cycle = Area ABCD

W = Area DCEH + Area BCEF − Area ABFH

$\frac{V_2}{V_1}$ = Exp. ratio

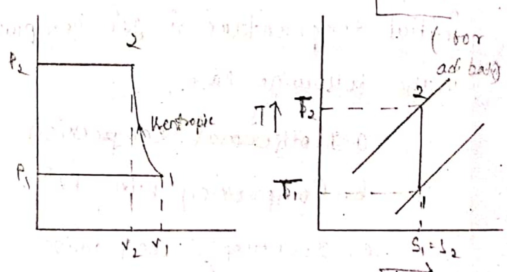
$\frac{V_1}{V_2}$ = comp. ratio

$$W = P_2 V_2 + 2.3 P_2 V_2 \log\left(\frac{V_1}{V_2}\right) - P_1 V_1 \qquad (\because P_1 V_1 = P_2 V_2)$$

$$W = 2.3 P_2 V_2 \log(r)$$

Workdone during isentropic compression/cycle :-

Isentropic : Reversible adiabatic.



$$W = \frac{r}{r-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{r-1}{r}} - 1 \right]$$

$$= \frac{r}{r-1} m R T_1 \left(\frac{T_2}{T_1} - 1 \right)$$

$$= \frac{r}{r-1} m R (T_2 - T_1)$$

$$= \frac{r}{r-1} \times m C_p \times \frac{r-1}{r} (T_2 - T_1)$$

$$\because C_p - C_v = R, \quad C_p \left(1 - \frac{C_v}{C_p}\right) = R, \quad C_p \left(1 - \frac{1}{r}\right) = R, \quad C_p \frac{(r-1)}{r} = R$$

$$W = m C_p (T_2 - T_1) \quad -(I)$$

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We know, $Q = mC_p(T_2 - T_1)$ --(ii)

from eq^n (i) & (ii)

Heat required to raise the temp. from T_1 to T_2 at const. pres. = W.D. during isentropic compression.

Power required :-

$$P = \frac{W N_w}{60} \text{ watts}$$

where N = Speed of the compressor.

then, $N_w = N$ (Single acting compressor)

$N_w = 2N$ (Double acting compressor)

where, N_w = no. of working strokes per minute

Question :-

1. A single stage reciprocating air compressor is required to compress 1 kg of air from 1 bar to 4 bar. The initial temperature is 27°c compared the work requirement in the following cases,

a. Isothermal compression

b. Compression with $PV^{1.2} = C$

c. Isentropic compression.

Given data, $m = 1$ kg

$P_1 = 1$ bar

$P_2 = 4$ bar

$T_1 = 27°c = 300$ K

Isoth. comp. $(W) = 2.3\, mRT_1 \log\left(\frac{P_2}{P_1}\right)$

$W = 2.3 \times 1 \times 287 \times 300 \times \log(4)$

$W = 119.22$ KJ

for polytropic, $n = 1.2$

$$W_{poly} = \frac{n}{n-1} \times (mRT_1)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{1.2}{0.2} \times 1 \times 287 \times 300 \times \left[(4)^{\frac{0.2}{1.2}} - 1\right]$$

$= 134.75$ KJ

for Isentrophic, $r = 1.4$

$$W_{isen.} = \frac{r}{r-1} \times mRT_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} - 1\right]$$

$$= \frac{1.4}{0.4} \times 1 \times 287 \times 300 \times \left[4^{\frac{0.4}{1.4}} - 1\right]$$

$= 146.45$ KJ

$\therefore W_{isoth.} < W_{poly.} < W_{adiab.}$

2. A single stage reciprocating air compressor is required to compress 60 m³ of air from 1 bar to 8 bar at 22°c. Find W.D by the compressor if compression of air is

a. Isothermal

b. Isentrophic

c. polytrophic with an index 1.25.

$V = 60 m^3$

$\rho_{air} = 1.293$

$\frac{m}{V} = \rho \Rightarrow m = \rho \times V = 1.293 \times 60 = 77.58$ kg

$P_1 = 1$ bar, $P_2 = 8$ bar

$T_1 = 22°c = 295$ K

for Isothermal,

$W = 2.3 \times mRT_1 \times \log\left(\frac{P_2}{P_1}\right)$

$= 2.3 \times 77.58 \times 287 \times 295 \times \log(8)$

$= 13.7 \times 10^6\ J$

$W = 2.3\ P_1V_1 \log(P_2/P_1)$

$= 2.3 \times 1 \times 10^5 \times 60 \times \log(8) = 12.46 \times 10^6\ J$

for isentropic,

$W = \frac{r}{r-1} \times P_1V_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} - 1\right]$

$= \frac{1.4}{0.4} \times 10^5 \times 60 \times \left[8^{\frac{0.4}{1.4}} - 1\right]$

$= \sout{42.067 \times 10^6\ J}$ $= 17.04 \times 10^6\ J$

for polytropic,

$W = \frac{n}{n-1} \times P_1V_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$= \frac{1.25}{0.25} \times 10^5 \times 60 \times \left[8^{\frac{.25}{1.25}} - 1\right]$

$= \sout{42.06 \times 10^6}\ J$

$= 15.47 \times 10^6\ J$

3. Find the power required to compress (2kg of air per minute) from 1 bar at 20°c to a delivery pressure 7 bar when the compression is carried out in a single stage compressor. Compression follows, $PV^{1.4} = C$. Neglate clearance.

$m = 2kg$

$P_1 = 1\ bar,\ P_2 = 7\ bar$

$T_1 = 20°c = 293c$

$r = 1.4$

$W = \frac{r}{r-1} \times mRT_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} - 1\right]$ KJ/min

$= \frac{1.4}{0.4} \times 2 \times 287 \times 293 \times \left[(7)^{\frac{0.4}{1.4}} - 1\right]$

$= \sout{497.45\ KJ}$ $437.73\ KJ/min.$

$\sout{P = \frac{W \times N_w}{60} = \frac{497.45 \times 1}{60} = 8.3\ KW}$

(∵ m = mass of fuel/stroke, mass of fuel = m; mass of fuel per minute = M; M = m × N)

$P = \frac{W}{60} = \sout{\frac{497.45}{60} = 8.29}$

$= \sout{\frac{437.73}{60} = 7.3\ KW}$

$= 437.73\ \frac{KJ}{60\ sec} = \frac{437.73}{60}\ KW = 7.3\ KW$

4. A single acting reciprocating air compressor has cylinder diam. & stroke of 200 mm & 300 mm respectively. The compressor sucks air at 1 bar and 27°c and delivers at 8 bar while running at 100 rpm. find

a. IP

b. mass of air delivered by the compressor per minute.

c. Temp. of the air delivered by the compressor.

Compression follows $P \times V_2^{1.25} = C$

Given data, $d = 200mm = 0.2m$

$l = 0.3m$

$P_1 = 1\ bar,\ P_2 = 8\ bar$

$T_1 = 300°K$

$N = 100\ rpm$

$V_1 = \frac{\pi}{4} d^2 \times l = \frac{\pi}{4} \times 0.2^2 \times 0.3 = 9.42 \times 10^{-3}$

$W = \frac{r}{r-1} \times P_1V_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} - 1\right]$

$= \frac{1.25}{0.25} \times 1 \times 10^5 \times 9.42 \times 10^{-3} \times \left(8^{\frac{0.25}{1.25}} - 1\right)$

$= 2.42\ KW$

a. $IP = \frac{N_w \times w}{60}$

$= \frac{100 \times 2.42 \times 10^3}{60}$

$= 4.0483750471 \text{ kW}$

c. b. $\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{r}{r-1}} \Rightarrow T_2 = \frac{T_1}{\left(\frac{P_1}{P_2}\right)^{\frac{r-1}{r}}} = \frac{300}{\left(\frac{1}{8}\right)^{\frac{0.25}{1.25}}} = 454.71 \text{ K}$

$= 181.71\,°C$

b. $\rho = \frac{m}{V}$

$\Rightarrow m = \rho \times V = 1.293 \times 9.42 \times 10^{-3}$

$= 0.01218$

So that mass of air is 0.01218 per stroke.

mass of air delivered per 1 minute is

$\Rightarrow m_{minute} = m \times N_w$

$\Rightarrow M = 0.01218 \times 100$

$\Rightarrow M = 1.218$

Technical terms used in compressor :-

I. Inlet pressure :-

It is the absolute pressure of air at the inlet of compressor.

II. Discharge pressure :-

It is the absolute pressure of air at the outlet of compressor.

III. Compression ratio (pressure ratio) :-

It is the ratio of discharge pressure to the inlet pressure

$\frac{\text{Discharge pressure}}{\text{Inlet pressure}} > 1$

IV. Compressor capacity :-

It is the volume of air delivered by the compressor

It's unit is m^3/min or m^3/sec

V. Free air delivery :-

→ It is the actual volume of air delivered by compressor when reduce to N.T.P condition.

→ The capacity of a compressor is generally given in-terms of free air delivery.

VI. Swept volume :-

→ It is the volume of air sucked by the compressor during it's suction stroke.

Mathematically, $V_s = \frac{\pi}{4} d^2 \times L$

VII. Mean effective pressure :-

$mep = \frac{W/cycle}{V_s}$

★ Effect of clearance volume :-

→ In actual practice it is not possible to reduce the clearance volume to zero due to mechanical ~~regions~~ reason. ~~besides~~

→ Besides it is not desirable to allow the piston head to come incontact with the cylinder head.

→ So generally clearance volume is provided as some percentage of the piston displacement.

W.D. of a R.A. compressor with clearance volume :-

Considering a reciprocating air compressor with clearance volume (V_c).

let, P_1, V_1 = Initial pres. & volume of air,

T_1 = " temp. of air

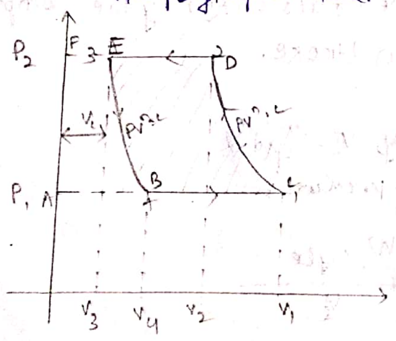
P_2, V_2, T_2 = corresponding pres, volume & temp. of air after compression.

$r = P_2/P_1$ = pressure ~~p~~ ratio.

$V_3 = V_c$ = clearance volume

Stroke volume $= V_1 - V_3$

n = polytropic index.



W.D by the compressor/cycle

= Area below BCDEB

= Area enclosed by ACDFA − Area enclosed by ABEFA

$= \frac{n}{n-1} P_1 V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right] - \frac{n}{n-1} P_1 V_4\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right]$

$= \frac{n}{n-1} P_1 (V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}-1\right]$

($V_1 - V_4$ = Actual vol^n of air sucked by piston/cycle.)

$V_1 - V_4$ is also known as effective swept volume

V_4 is expanded clearance volume.

Clearance volume doesn't effect the W.D on air & the power require for compressing the air because the reason required to compress the clearance volume air is theoratically regained during it's expansion.

Question:

A single stage single acting R.A. compressor has a bore of 200 mm & a stroke of 300mm. It receives air at 1bar & 20°C & delivers it at 5.5 bar. If the compression follows $pv^{1.3} = c$ & clearance volume is 5% of stroke volume determine

(i) MEP (P_m)

(ii) Power required to drive the compressor if it runs at 500 rpm.

Given data, d = 200 mm = 0.2 m

l = 300mm = 0.3 m

P_1 = 1 bar

T_1 = 20°C = 293 K

P_2 = 5.5 bar

$V_s = \frac{\pi}{4} d^2 l = \frac{\pi}{4} \times 0.2^2 \times 0.3$

$= 9.42 \times 10^{-3} m^3$

~~Process, 4-1~~ , P = const.

~~$\frac{V_4}{T_4} = \frac{V_1}{T_1}$~~

Given, $V_c = 5\% \times V_s$

$= 0.05 \times 9.42 \times 10^{-3}$

$= 4.71 \times 10^{-4} m^3$

$V_1 = V_c + V_s = 9.89 \times 10^{-3} m^3$

Process, 3-4

$P_2 V_3^n = P_1 V_4^n$

$\Rightarrow V_4^n = \left(\frac{P_2}{P_1}\right) \times V_3^n$

$\Rightarrow V_4 = \left(\frac{P_2}{P_1} \times V_3^n\right)^{1/n} = \left(\frac{P_2}{P_1}\right)^{1/n} \times V_3$

~~$= \left(\frac{5.5}{1}\right)^{1/3} \times 4.71 \times 10^{-4}$ ($\because V_3 = V_c$)~~

~~$= 8.31 \times 10^{-4} m^3$~~ ($\because V_3 = V_c$)

$= \left(\frac{5.5}{1}\right)^{1/1.3} \times 4.71 \times 10^{-4}$

$= 1.74 \times 10^{-3}$

$W = \frac{n}{n-1} \times P_1 (V_1 - V_4) \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$= \frac{1.3}{0.3} \times 1 \times 10^5 \times (9.89 \times 10^{-3} - 1.74 \times 10^{-3}) \times \left[\left(\frac{5.5}{1}\right)^{\frac{0.3}{1.3}} - 1\right]$

~~= 1702 J~~ = 1702.3 J

$P = \frac{1702 \times 500}{60} = 14186$ Watt

$mEP = \frac{W}{V_s}$

$= \frac{1702}{9.42 \times 10^{-3}} = 180679.4$ Pa

$= 1.8$ bar

Multistage Compression :-

Purpose :-

If we employ single stage compression for producing high pressure air, it suffers from followings

i) Size of cylinder will be too large

ii) Due to compression there is a rise in temperature of the air. It is difficult to reject heat from the air in the small time available during compression.

iii) Some times temperature of the air at the end of compression is too high that it may leads to cylinder damage or burning of lubricating oil.

Advantages :-

→ It reduces the leakage loss considerebly.

→ It provides effective lubrication.

→ It reduces the cost of ~~compression~~ compressor.

→ It improves the volumatric efficiency for a given pressure ratio.

→ W.D per kg of air is reduced in multistage compression with the use of intercooler.

→ Size of cylinders may be adjusted to shoot the volume & pressure of the air.

Intercooler :-

It is a mechanical device used to pull a gas after compression in first cylinder. It typically takes the form of heat exchanger that removes ~~heat~~ west heat in

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a gas compressor.

-> Compressing a gas increases ~~increa~~ it's internal energy which ~~for~~ inturn raises it's temperatures & reduces it's density.

-> Removing the heat of compression (from the distance) the 1st stage has the effect of densifying the air.

Second stage R.A. compressor with intercooler:-

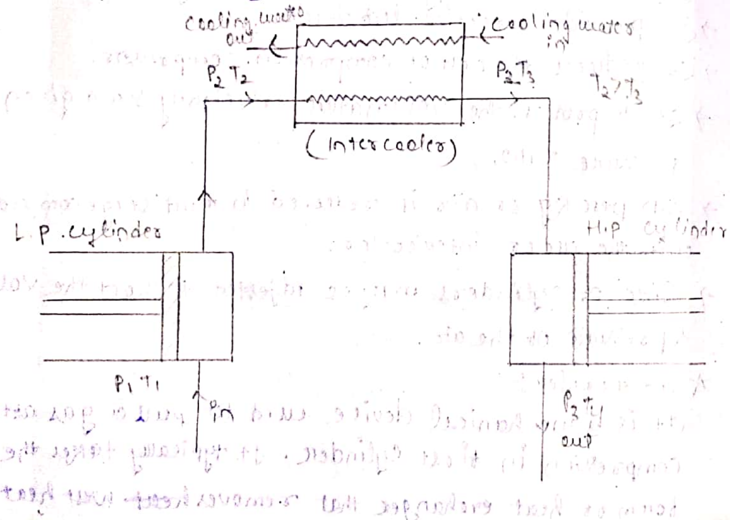
-> First of all the air is sucked from the atmosphere into the low pressure cylinder during the suction stroke at intake pressure P_1.

-> In the low pressure cylinder air after compression is delivered to the intercooler at P_2 & T_2.

-> Now the air is cooled in the intercooler at constant pressure P_2 and temperature from T_2 to T_3.

-> After that air enters to the high pressure cylinder during it's suction stroke & compression occurs to pressure P_3.

-> Finally the air is delivered at by the compressor at pressure P_3 + temperature T_4.



Assumption:-

-> Effect of clearance is neglected.

-> There is no pressure drop in the intercooler.

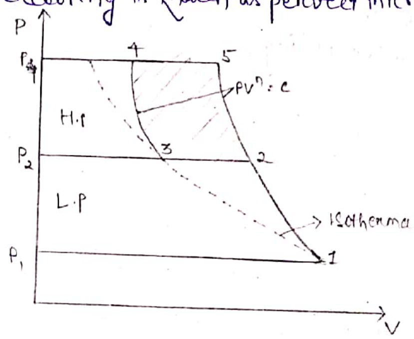
-> Compression in both the cylinder is polytropic.

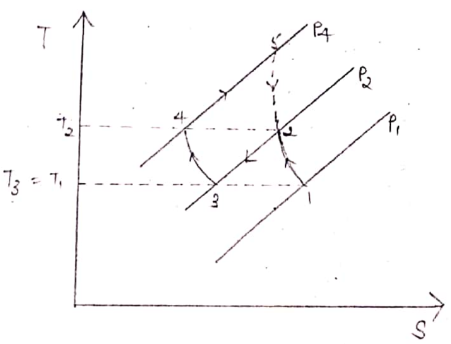
-> Suction & delivery of air takes place at constant pressure.

Case-1:-

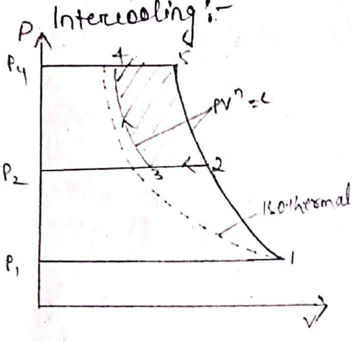
Perfect inter cooling:-

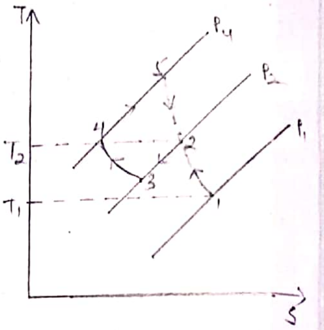
When the temperature of the air leaving the intercooler (T_3) is equal to the original atmospheric air temperature (T_1) then the intercooling is known as perfect intercooling.





Case-2 :- Intercooling :-





Problems:-

1. 2 stage single acting R.A compressor draws in air at a pressure of 1 bar at 17°c & compresses it to a pressure of 60 bar. after compression in the L.P cylinder the air is cooled at constant pressure of 8 bar to a temp. of 37°c. The L.P cylinder has a diameter of 150mm & both the cylinders have 200 mm stroke. If the law of compression is $PV^{1.35}=C$. find the power of the compressor when it runs at 200 rpm? $R = 287\ J/kgK$.

Given data, $P_1 = 1$ bar

$T_1 = 290K$, $T_3 = 37°c = 310K$

$P_3 = 60$ bar, $d_1 = 150mm$, $V_1 = 3.53\times10^{-3}\ m^3$

$P_2 = 8$ bar, L_1 & $L_2 = 200mm$

$n = 1.35$

$N = 200$ rpm

$R = 287\ J/kgK$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n$$

$$\Rightarrow V_2 = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} \times V_1$$

$$= \left(\frac{1}{8}\right)^{\frac{1}{1.35}} \times 3.53\times10^{-3}$$

$$= 7.56\times10^{-4}\ m^3$$

$$W_a = \frac{n}{n-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{1.35}{0.35} \times 1\times10^5 \times 3.53\times10^{-3} \times \left[\left(\frac{8}{1}\right)^{\frac{0.35}{1.35}} - 1\right]$$

$$= 972.82\ J$$

$$W_b = \frac{n}{n-1} P_2V_2\left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{1.35}{0.35} \times 8\times10^5 \times 7.56\times10^{-4} \times \left[\left(\frac{60}{8}\right)^{\frac{0.35}{1.35}} - 1\right]$$

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$W_B = 1600.4 J$

$P = \frac{W \times N_w}{60}$ watt

$= \frac{(972.82 + 1600.4) \times 200}{60} = 8577.4$ watt

Minimum work required for 2 stage R.A compressor

In case of perfect intercooling

$$W = \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

If intake pressure P_1 & delivery pressure P_3 are fixed then least value of P_2 (intercooler pressure) may be obtained by differentiating 'W' w.r.t P_2.

The obtained value for P_2 will give us the minimum work required;

Thus minimum work is required when $\frac{dw}{dP_2} = 0$

Assuming $\frac{n-1}{n} = t$

$$W = \frac{n}{n-1} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_4}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

$$\frac{dw}{dP_2} = \frac{d}{dP_2}\left[\frac{1}{t} P_1V_1 \left[\left(\frac{P_2}{P_1}\right)^{t} + \left(\frac{P_4}{P_2}\right)^{t} - 2\right]\right] = 0$$

$\because \frac{P_2^t}{P_1^t} = P_2^t \cdot P_1^{-t}$

$= P_2^t \times t \cdot P_1^{-t-1}$

$= P_2^t \times t P_1^{-(t+1)}$

$= \frac{tP_2^t}{P_1^{t+1}}$

$$\Rightarrow = \frac{1}{t} P_1V_1 \left[\frac{1}{P_1^t}\frac{d}{dP_2} P_2^t + P_4^t \cdot \frac{d}{dP_2} P_2^{-t} - 2\right] = 0$$

$\Rightarrow P_1^{-t} \cdot t \cdot P_2^{t-1} + P_4^t \cdot -tP_2^{-(t+1)} - 0 = 0$

$\Rightarrow P_1^{-t} P_2^{t-1} = P_4^t \cdot P_2^{-(t+1)}$

$\Rightarrow P_2^{(t-1)} \cdot P_2^{(t+1)} = P_4^t \cdot P_1^t$

$\Rightarrow P_2^{2t} = (P_4P_1)^t$

$P_2^2 = P_4 P_1$

$\Rightarrow P_2 = \sqrt{P_4 P_1}$

Also, $P_2^2 = P_4 P_1$

$$\frac{P_2}{P_1} = \frac{P_4}{P_2}$$

$$\frac{P_2}{P_1} = \frac{P_4}{\sqrt{P_4P_1}}$$

$$\frac{P_2}{P_1} = \frac{\sqrt{P_4}}{\sqrt{P_1}}$$

Now minimum work required.

$$\frac{n}{n-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 2\right] \quad \left(\because \frac{P_4}{P_2} = \frac{P_2}{P_1}\right)$$

$$\frac{n}{n-1} P_1V_1\left[2\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 2\right]$$

313 bar , 73.2 kW

Exercise :-

9. A two stage reciprocating air compressor delivers 40.5 kg/min at 9.8 bar. The intake pressure is 1 bar and intake temperature is 15.5°C. The compression follows $pv^{1.31}$ = C & the intercooler cools the air back to the intake temperature. Neglecting clearance, calculate

1. The optimum intermediate pressure
2. The power to be delivered to each cylinder
3. & 3. The rate of heat transfer from the cylinders & intercooler.

Given data,

P_1 = 1 bar

T_1 = 15.5°C = 288.5 K

r = 1.31

T_3 = T_1 = 288.5 K

P_3 = 9.8 bar

for water

P_{cr} = 22.6 MPa

T_{cr} = 373°C

Formation & properties of steam :-

Gas :-

A Gas refers to a substance that has a single defined thermodynamic at room temp.

Vapour :-

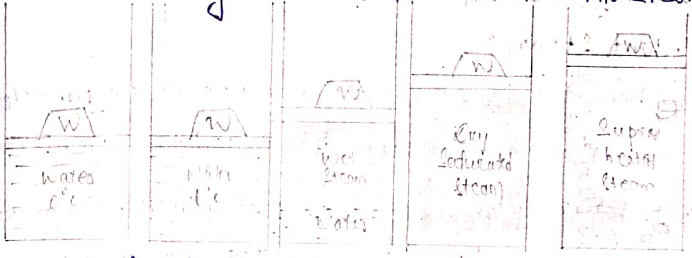
Vapour refers to a substance that is a mixture of two phases at room temp.

Steam :-

It is a vapour into which water is converted when heated.

Formation of steam :-

Considering water at 0°C contained in a piston cylinder arrangement. The piston end weights maintain a constant pressure in the cylinder. Now heating of water will converted into steam.



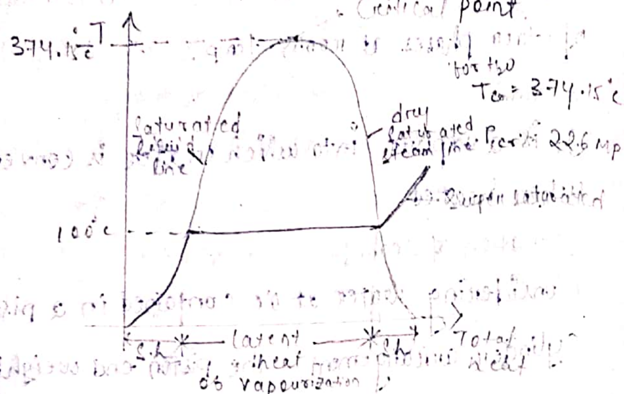
→ As heating contineous the temp. equel to the boiling temperature then temp. remains same & evaporation of water takes place, leads to upward movement of piston.

→ At this stage steam will have some particles of water in suspension. At the end of this process the whole water is converted into wet steam.

-> On furthere heating the water particles in suspension will be converted into steam. At this state the steam is known as dry steam.

-> If more heat is supplied temp. of saturated steam increases & this stage is known as super heated steam.

Temp. w.r.t Total heat curve:-



Important terms for steam :-

~~1. Weight steam~~ :-

1. Wet steam :-

-> When the steam contains moisture or particles of water in suspension it is called to be wet steam.

-> It means evaporation of water is not completed & whole of the latent heat has not been absorved.

II. Dry saturated steam :-

When the steam is heated up to a point where it doesn't contain any suspended water particles is called as dry saturated steam & it behaves pratically like a perfect gas.

III. Super heated steam :-

When the dry steam is furthere heated at a constant pressure it raises it's temperature it is called as superheated steam.

IV. Dryness fraction (or quality of wet steam) :-

It is the ratio of mass of actual dry steam to the mass of wet steam & is generally deonated by x.

$$x = \frac{m_g}{m_f + m_g}$$

where, m_g = mass of actual dry steam

m_f = mass of suspended water particles in steam

m = mass of wet steam.

Sensible heat of water :- (liquid heat.)

-> It is the amount of heat aborsorbed by 1kg of water when heated at constant pressure from the freezing point to the temp. of formation of steam.

-> It is also known as liquid heat.

$$Q = mc\Delta(T_2 - T_1)$$

$$= mc\Delta t$$

$$= 1 \times 4.2 \times [(t + 273) - 273] \quad (\because c = 4.2 \text{ for water})$$

$$= 4.2t \text{ KJ/kg}$$

Latent heat of vapourization (h_{fg}) :-

-> It is the amount of heat absorved to evaporate 1 kg of water at it's boiling point or saturation temperature with out changing the temperature.

-> It is deonated by h_{fg}

-> It's value depends on pressure and from experie- -ments it is absorved that with increase in pressure

h_{fg} is decreases and h_{fg} is equal to zero at critical point.

→ If the steam is wet with the dryness fraction x then the heat is absorved by it $x h_{fg}$.

Enthalpy:-

→ It is the amount of heat absorved by water from freezing point to saturation temperature & the heat absorved during evaporation.

→ It is deonated by h_g.

(i) Wet steam :- The enthalpy of wet steam is given by $h_f + x h_{fg}$.

(ii) Dry steam :- The enthalpy of dry steam

$$h_g = h_f + h_{fg}$$

(iii) Superheated Steam :-

~~h_{sup} — h_g~~

h_{sup} = Total heat of dry steam + Heat for superheated steam

$$h_{sup} = h_g + m.C_p(t_{sup} - t)$$

$$\boxed{h_{sup} = h_f + h_{fg} + C_p(t_{sup} - t)} \quad (\because m = 1)$$

★ Degree of superheat = $t_{sup} - t$

★ value of C_p of superheated steam = 1.67 – 2.5 kJ/kg K

Specific volume of steam ($\forall$) :-

→ It is the volume occupied by the steam per unit mass at a given temp. & pressure & is expressed in m^3/kg.

→ It is deonated by $\forall$

★ $\boxed{\forall = \frac{1}{\rho}}$

→ The value of sp. volume decreases with increase pressure

~~Wet steam :-~~

(i) Sp. volume of wet steam :-

$$x = \frac{dry}{total}$$

x = dry $\quad$ ($\because$ it is total = 1 kg of mass)

wet = $1 - x$.

Sp. volume of wet steam.

$$\boxed{\forall = x\forall_g + (1-x) V_f}$$

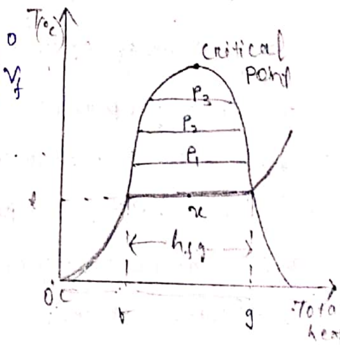
Then,

$$\forall = x\forall_g + (1-x) V_f$$

$\because$ $V_g >>> V_f$

and V_f is negligible.

So, $\boxed{\forall = x\forall_g}$



(ii) Sp. volume of dry steam :-

for dry steam sp. volume, $\boxed{\forall = \forall_g}$

(iii) Sp. volume of superheated steam :-

In super heated steam, $P_g = C$ ($\because P_g = P_{sup} = C$)

So. $\frac{P_g V_g}{T_{sat}} = \frac{P_{sup} \cdot V_{sup}}{T_{sup}}$

$$\Rightarrow \boxed{V_{sup} = \frac{V_g \times T_{sup}}{T_{sat}}}$$

Where, V_g = sp. vol. of dry steam.

V_{sup} = sp. vol. of ~~wet~~ superheated steam.

T_{sat} = temp. of saturated steam

T_{sup} = temp. of superheated steam

○ Steam table :-

→ The properties of dry saturated steam like temp. of formation or saturation temp (T_{sat}), sensible heat, latent heat of vapourization, enthalpy, sp. volume entropy etc. vary with pressure, can be found by experiments only.

→ These properties have been carefully obtained/ determined in a tabular form called steam table.

→ There are two important steam tables one in terms of saturation temperature & other in terms of absolute pressure.

Question :-

1. Calculate the enthalpy of 1kg of steam at a pres. of 8 bar and dryness fraction of 0.8. How much heat could be required to raise 2kg of this steam from water at ~~32~~20°C.

Given data, $m = 1kg$.

$P = 8 bar$

$x = 0.8$ $h_{x=0.8} = ?$

from steam table, at $P = 8$ bar

$h_f = 720.9$ kJ/kg

$h_{fg} = 2046.5$ kJ/kg

Then, $h_{x=0.8} = 720.9 + 0.8 \times 2046.5$

$= 2358.1$ kJ/kg, for 1kg, $h_{x=0.8}$ $= 2358.1$ kJ

Heat available with water at 20°C from 1kg

$Q = 4.2 \times \Delta t$

$Q = 4.2 \times ((20 + 273) - (0 + 273))$

$= 4.2 \times 20$

$= ~~1230.6~~ kJ = 84$ kJ

Heat required $= 2358.1 - ~~1230.6~~ 84$

$= ~~1127.5 kJ~~ = 2274.1$ kJ

For 2kg of steam $= 2274.1 \times 2 = 4548.2$ kJ ~~1127.5 × 2 = 2255 kJ~~

2. ~~Det~~ Determine the Quantity of heat required to produce 1kg of steam at a pres. of 6 bar at a temp. of 25°C under the following condition.

(i) when the steam is wet having a dryness fraction 0.9

(ii) when the steam is dry saturated

(iii) when it is superheated at a const. pressure to 250°C. assuming mean sp. heat of superheated steam to be 2.3 kJ/kgK

Given data, $m = 1\,kg$

$P = 6$ bar

$t = 25°c$

i) When steam is wet
For 1kg of steam,

$h = h_f + x h_{fg}$

$= 670.4 + 0.9 \times 2085$

$= 2546.9$ KJ

Heat available with water at 25°c for 1kg.

$Q = C.\Delta t$

$= 4.2 \times 25$

$= 105$

∴ Heat actually required $= 2546.9 - 105 = 2441.9$ KJ

ii) When steam is dry saturated

$h_g = h_f + h_{fg} = 670.4 + 2085$

$= 2755.4$ KJ

∴ Heat required $= 2755.4 - 105$

$= 2650.4$ KJ

iii) When steam is of superheated.

$h_{sup} = h_g + c_p(t_{sup} - t_{sat})$

$= 2755.4 + 2.3 \times (250 - 158.8)$

$= 2755.4 + 209.76$

$= 2965.16$ KJ

∴ Heat required $= 2965.16 - 105$

$= 2860.16$ KJ

3. Determine the condition of steam in the following Cases.

① At a pres. of 10 bar & volume of 0.175 m^3/kg

② At a pres of 10 bar & temp. 200°c

Given data,

① At 10 bar, $v_{fg} = 0.175\ m^3/kg$

$v_g = 0.194\ m^3/kg$

In this, $v < v_g$ → wet steam

$x = \frac{v}{v_g} = \frac{0.175}{0.194} = 0.902$ $\left(\because x = \frac{m_g}{m}\right)$

② 10 bar, $t = 200°c$

At 10 bar; $T_{sat} = 179.9°c$

$T > T_{sat}$

∴ The condition is superheated.

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4. Steam enters at engine at a pres. of 12 bar with a 67°c of superheat. It is exerted at a pres. of 0.15 bar & point 0.95 dry. Find the drop in enthalpy in the steam. $c = 2\,KJ/kg\,K$

Given data, $P_1 = 12$ bar

~~$T_{sup} = 67°c$~~

$T_{sup} - T_{sat} = 67°c$

$h_g = 2782.7$ KJ

$h_1 = h_f + h_{fg} + C(T_{sup} - T_{sat})$

$= h_g + C(T_{sup} - T_{sat})$

$= 2782.7 + 2 \times 67$

$= 2916.7$ KJ

$P_2 = 0.15$ bar, $x = 0.95$

$h_2 = h_f + x h_{fg}$

~~$= 226 + 0.95 \times 2373.2$~~

$= 226 + 0.95 \times 2373.2$

$= 2480.54$ KJ

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$\therefore$ Drop in enthalpy, $h = h_1 - h_2$

$= 2916.7 - 2480.54$

$= 436.16$ kJ

5. A steam engine obtains steam from a boiler at a press. of 15 bar and 0.98 dry. It was observed that the steam looses 21 kJ of heat per kg as it flows through the pipe line press. remaining constant. Calculate the dryness fraction of steam at the engine end of the pipeline.

$P_1 = 15$ bar

$x = 0.98$ dry

$h_1 = h_f + 0.98\, h_{fg}$

$= 844.6 + 1945.3 \times 0.98$

$= 2751$ kJ/kg

$h_2 = h_1 - h = 2751 - 21$

$= 2730$ kJ/kg

$h_2 = h_f + x h_{fg}$

$x h_{fg} = h_2 - h_f$

$x = \frac{h_2 - h_f}{h_{fg}} = \frac{2730 - 844.6}{1945.3}$

$= 0.969 \approx 0.97$

Advantages of superheating steam :-

→ It contains more heat contents. Hence it's capacity to do work is increased without increasing the pressure.

→ The superheating is done in a superheater which uses the waste heat from furnace gases.

→ The high temp. of the superheated steam results in increasing thermal efficiency. $\eta = \frac{W}{Q}$

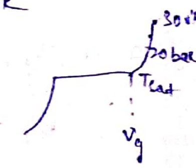
6. Determine the vol. of 1 kg of superheated steam at a press. of 20 bar and a temp. of 300°C.

$P_1 = 20$ bar

$T_{sup} = 300°C = 573$ K

& S.T. $T_{sat} = 212.4°C = 485.4$ K

S.T. $v_g = 0.09955\ m^3/kg$



At $P = C$

$\frac{v_g}{T_{sat}} = \frac{v_{sup}}{T_{sup}}$

$v_{sup} = \frac{v_g}{T_{sat}} \times T_{sup}$

$= \frac{0.0955}{485.4} \times 573$

$= 0.1175\ m^3/kg$

7. A boiler is supplied with a feed water at a temp of 45°C. The water is converted into steam at a press. of 5.5 bar and a temp. of 188°C. Determine the quantity of heat supplied per kg of steam. $C = 2.1$ kJ/kg

$P = 5.5$ bar

$h_{f\,5.5} = \dfrac{h_{f\,5.4} + h_{f\,5.6}}{2}$

$=$

$= 655.8$ KJ/kg

$h_{fg\,5.5} = \dfrac{h_{fg\,5.4} + h_{fg\,5.6}}{2}$

$=$

$= 2095.9$ KJ/kg

$T_{sat} =$

$= 155.5'C$

$h_{f\,5.5} = 655.8$ KJ/kg

$h_{fg\,5.5} = 2095.9$ KJ/kg

$T_{sat} = 155.5'C$

given, $T_{sup} = 188°C$

$h_1 = h_g + C_{sup}(T_{sup} - T_{sat})$

$= (655.8 + 2095.9) + 2.1(188 - 155.5)$

$= 2820$ KJ/kg

energy available in water,

$Q = 4.2 \times (45 - 0)$

$= 189$ KJ

∴ The Quantity of heat required $=$

$= 2820 - 189 = 2631$ KJ

21/6/23
Ch, 2-5

Exercise :-

1. 5 Kg of steam at a press. of 5 bar is produced from water at 20°c. Determine the amount of heat supplied, if the steam is 0.9 dry.

Given data, $m = 5$ Kg

$P_1 = 5$ bar

$t = 20'c$

$x = 0.9$

S.T. $h_f = 640.23$

$h_{fg} = 2108.5$

$h = h_f + 640.23 + 0.9 \times 21088.5$

$= 2537.88$ KJ/kg

Heat available in water, $Q = 4.2 \times 20$

$= 84$ KJ/kg

∴ The heat required $= 2537.88 - 84$

$= 2453.88$ KJ/kg

For 5 kg, $Q = 2453.88 \times 5 = 12269.4$ KJ

2. Find the amount of heat required to convert 1kg of steam at a pressure of 0.5 bar and dryness fraction 0.9 to dry staturated steam.

Heat available in the steam,

$h = h_f + 0.9 \times h_{fg}$ (S.T.)

$= 340.49 + 0.9 \times 2305.4$

$= 2415.76$

$h_g = 2645.9$

∴ The heat required to the steam $= 2645.9 - 2415.76$

$= 230.14$ KJ

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5. A certain amount of steam is produced at a pressure of 8 bar and a dryness fraction 0.8. Determine :

(i) External w.D during evaporation.

(ii) Internal latent heat of steam.

Heat available in steam,

$h = 721.11 + 0.8 \times 2048$

$= 2359.51$

External W.D during evaporation :-

The latent heat is utilised in the following two ways.

→ In overcoming the internal molecular resistance of water in changing it's state from the saturated water to dry saturated steam. → (Internal work or Internal latent heat) / (energy stored in the steam)

→ In overcoming the external resistance to the movement of piston due to the increase in volume during evaporation → (External W.D of evaporation / energy which have been taken out of the steam)

Let p = pressure in the piston, in bar

v_f = Volume of water at pressure 'p', in m^3

v_g = volume of steam at pressure 'p', in m^3

W.D during evaporation, $W = p(v_g - v_f)$

$W = p \times 10^5 (v_g - v_f)$ J

$W = 100p (v_g - v_f)$ KJ

At low pressure, $v_g >>> v_f$

So v_f is negligible & it becomes zero.

$\therefore W = 100p(v_g - v_f)$ KJ

$W = 100 p v_g$ KJ

In case of superheating to v_{sup}.

$W = 100 p v_g + 100 p (v_{sup} - v_g)$

$W = 100\cancel{p}v_g + 100p\,V_{sup} - 100\cancel{p}v_g$

$W = 100p\,V_{sup}$ KJ

If steam is wet,

$W = 100p\,x\,v_g$

1. Find the external W.D during evaporation per kg of steam at a pres. bar 15 bar when the steam is

a. 90' dry

b. dry saturated.

P = 15 bar

S.T. $v_g = 0.13177$

a. W.D = ~~100pvg~~ $100p\,x\,v_g$

$= \cancel{100}15\times10^5 \times 0.9\times0.13177$

$= 177889.5$ J/kg

$= 177.8$ KJ/kg

b. W.D = $100p\,v_g$

$= 1000\times15\times10^5\times0.13177$

$= 197655$ J/kg

$= 197.6$ KJ/kg

Internal energy of steam :-

→ It is the actual internal energy stored in the steam above the freezing of water.

Mathematically ;

Internal energy of steam = (Enthalpy or total heat − External work during evaporation)

→ For wet steam = $h_f + xh_{fg} - 100p\,x\,v_g$ (KJ/kg)

→ For dry saturated steam = $h_g - 100p\,v_g$ (KJ/kg)

→ For superheated steam = $h_g + C_{sup}(T_{sup} - T_{sat}) - 100p\,V_{sup}$ (KJ/kg)

Question :-

Find the internal energy of 1kg of superheated steam at a pres. of 10 bar & temp. 280°C. If this steam ~~will~~ be expanded to a pres. of 1.6 bar & 0.8 dry. Determine the change in internal energy.

Assuming, $C_{sup} = 2.1$ KJ/kgK

Given data, m = 1kg

p = 10 bar

T = 280°C

S.T. , $h_g = 2778.1$ KJ/kg , T = 179.91

$v_g = 0.19444$ m³/kg

~~$h = h_g \cdot h_f + h_g$~~ $h_g - 100p\,v_g$

~~$= 2778.1 - 100\times10\times10^5\times0.19444$~~

=

$h_{sup} = 2778.1 \cancel{+} 2.1\,(280 - 179.91)$

$= 55.89\times10^6$

energy stored in the steam $= 4.2\times280 = 1176$

$h_{sup} = 2778.1 + 2.1\,(280 - 179.91)$

$= 2988.229$ kJ/kg

$V_{sup} = \frac{V_{sat}}{T_{sat}} \times T_{sup}$

$= \frac{V_g}{T_{sat}} \times T_{sup}$

$= \frac{0.19444}{179.91} \times 280 = 0.2374$

~~= 0.3026 m³/kg~~

$U_1 = 2988.229 - 100 \times 10 \times 0.3026$

~~= 2685.629~~

$= 2750.829$ kJ/kg

Then it's expanded to a pressure, P = 1.6 bar

x = 0.8

$U_2 = h_f + x h_{fg} - 100\,p\,x\,V_g$

$= 475.36 + 0.8 \times 2221.1 - 100 \times 1.6 \times 0.8 \times 1.0914$

$= 2112.54$ kJ/kg

∴ change in internal energy, $du = U_1 - U_2$

$= 2750.829 - 2112.54$

$= 638.3482$ kJ/kg

Entropy of System :-

The entropy of steam increases with addition of heat and decreases with it's removal.

Entropy of steam consists of

1. Increase in entropy of water during heating from freezing point to boiling point corresponding to the pressure at which water is heated.
2. Increase in entropy during evaporation.
3. Increase in entropy during superheating.

Entropy of water :-

Considering 1 kg of water during heated at constant press from freezing point to boiling point. Now at an instant, the absolute value of water will be T K.

Let there be a small change rise in temperature dT, heat absorbed by 1 kg of water is δQ.

$\delta Q = 1 \times C_w \times dT$ (C_w = sp. heat of water)

$\boxed{\delta Q = C_w dT}$

Note: $C_w = 4.2$ kJ/kg-K

Entropy of water at '0°C' is equal to zero.

$\boxed{\ln = \log_e = 2.3 \log_{10}}$

Increase in entropy, $ds = \frac{\delta Q}{T}$

$\Rightarrow ds = \frac{C_w dT}{T}$

Integrating we get total entropy from temp. 0 to T K

$\Rightarrow \Delta S = \int_{S_1}^{S_2} ds = \int_{273}^{T} \frac{C_w dT}{T}$

$\Rightarrow \Delta s = C_w [\ln T]_{273}^{T}$

$= C_w \times \ln T - \ln 273$

$\Delta s = C_w \ln \frac{T}{273}$ $(\because \Delta s = s_f - 0)$

$\Rightarrow$ $\boxed{\Delta s_f = 2.3 \times C_w \log\left(\frac{T}{273}\right)}$

Entropy increase during evaporation :-

When the water is completely evaporated into steam, it absorbs full latent heat (h_{fg}) at constant temperature corresponding to the given pressure.

Entropy $= \frac{\text{Heat absorved}}{\text{Absol. Temp.}}$

Increase in entropy during evaporation $= \frac{h_{fg}}{T_{sat}}$ $\Rightarrow \boxed{S_{fg} = \frac{x\, h_{fg}}{T_{sat}}}$

If the steam is wet with dryness fraction 'x' (partial evaporation),

Heat absorbed $= x h_{fg}$ $(\Delta s = s_f - s_g = s_{fg})$

$\therefore$ Increase in entropy, $\Delta s = \frac{x\, h_{fg}}{T_{sat}}$ $\Rightarrow \boxed{S_{fg}/_x = \frac{x\, h_{fg}}{T_{sat}}}$

Entropy of Wet & Dry steam :-

Entropy of dry steam $= S_g$

$S_g = S_f + S_{fg}$

Entropy of wet steam $(0<x<1)$,

$S_{fg}/_x = S_f + x \frac{h_{fg}}{T_{sat}}$

$\Rightarrow \boxed{S_{fg}/_x = S_f + x S_{fg}}$

Entropy of superheated steam :-

for a small rise dT,

$\delta Q = C_p dT$

where, C_p = specific heat of superheated steam,

$C_p \rightarrow 1.67$ to 2.5 kJ/kgK

$\Rightarrow \frac{\delta Q}{T_{sat}} = \frac{C_p dT}{T_{sat}}$

$\Rightarrow ds = C_p \frac{dT}{T_{sat}}$

Integrating both sides,

$\Rightarrow \int_{s_g}^{s_{sup}} ds = C_p \int_{T_{sat}}^{T_{sup}} \frac{dT}{T}$

$\Rightarrow s_{sup} - s_g = 2.3\, C_p \log\left(\frac{T_{sup}}{T_{sat}}\right)$

$\Rightarrow \boxed{S_{sup} = S_g + 2.3\, C_p \log\left(\frac{T_{sup}}{T_{sat}}\right)}$

Question :-

Calculate the entropy of 1kg of steam with dryness fraction 0.9 at 20 bar.

$S_{fg}/_{x=0.9} = S_f + x S_{fg}$ kJ/kg

$= 2.4474 + 0.9 \times 3.8935$

$= 5.95155$ kJ/kg K

Determine the entropy per kg of superheated steam at constant pres. of 20 bar & temp. of 250°C & given C_p value is 2.2 kJ/kg K.

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$S_{sup} = S_g + 2.3\, c_p \log\left(\frac{T_{sup}}{T_{sat}}\right)$

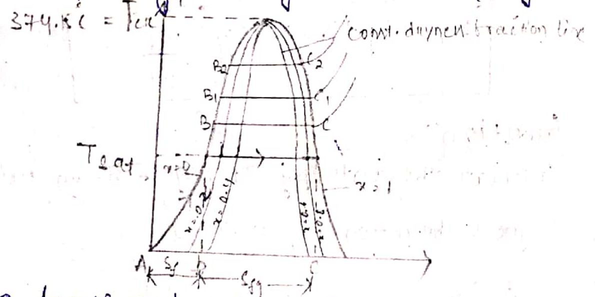
$= 6.3409 + 2.3 \times 2.2 \times \log\left(\frac{250+273}{212.42+273}\right)$

$= 6.50$ kJ/kg

Temperature - Entropy (T-s) for water & steam:-

The abscissa (x-axis) of the diagram represents the entropy of 1kg of water & steam above the freezing point of water. The ordinate (y-axis) shows the value of temperature.

If a graph is plotted betn 'T' & 's' in case of addn of heat into water. The entropy increases along logarithmic curve with the increase in temp. still the boiling temp (T_{sat}) corresponding to pressure 'p' is reached. Corresponding entropy S_f is shown by AB.



On furthere heating water starts evaporating on constant temp. 'T' receiving latent heat supplied to the water of 1kg.

The corresponding entropy change is given by the line bc is equel to S_{fg}.

Constant press. process:-

$W_{1-2} = 100p\,(v_2 - v_1)$

$\delta Q = du + W_{1-2}$

$= h_2 - 100pv_2 - h_1 + 100pv_1 + 100pv_2 - 100pv_1$

$\delta Q = h_2 - h_1$

$\Delta h = mc_p\Delta t$, $\Delta U = mc_v\Delta t$

Question:-

1. 1kg of steam at a press. of 17.5 bar & dryness 0.95 is heated at a const. press. until it is completly dry. Determine

I. The increase in volume

II. Quantity of heat supplied.

III. Change in entropy.

$P = 17.5$ bar

$x_1 = 0.95$

$x_2 = 1$

1. $v_1 = x_1 v_{g_1} = 0.95 \times 0.11340$

$= 0.10773$ m³/kg

for $m = 1$kg,

$V_1 = 0.10773\,m^3$

$v_2 = x_2 \times v_{g_1} = 1 \times 0.11340 = 0.11340$ m³/kg

for m = kg,

$V_2 = 0.11340\,m^3$

Increase in volume, $V_2 - V_1 = 0.11340 - 0.10773$

$= 5.67 \times 10^{-3}\,m^3$

b. $W_{1-2} = \cancel{100 p V_2 - 100}\ 100 p (V_2 - V_1)$

$= 100 \times 12.5 \times 5.75 \times 10^{-3}$

$= 9.9225$ KJ

$h_1 = h_{f_1} + x h_{fg_1}$

$= 875.2 + 0.95 \times 1915.9$

$= 2698.305$ KJ

$h_2 = h_{f_2} + x h_{fg_2}$

$= 878.2 + 1 \times 1915.9$

$= 2794.1$

ii. → $SQ = h_2 - h_1 = 2794.1 - 2698.305$

$= 95.8$ KJ

iii. $S_{f_1} = 2.384 + 0.95 \times 4.001$

$= 6.184$ KJ

$S_{fg} = 6.389$ KJ

$\Delta S = 6.385 - 6.184$

$= 0.20005$ KJ

3. constant temp. process :-

Question :-

Steam at a pres. of 5.4 bar and dryness fraction 0.8 expands in a cylinder reversibly & isothermally to a press. of 1 bar. Find

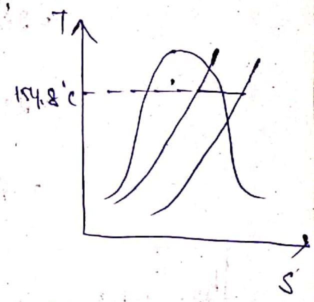
i. Final condition of steam

ii. change in internal energy.

iii. change of entropy

iv. Heat transfer

v. Workdone per kg.



Given data, $P_1 = 5.4$ bar

$x_1 = 0.8$

$P_2 = 1$ bar

S.T. $T = 154.8$

i) Find in final condition of steam :-

From ~~steo~~ steam table, T_{sat} at p_1 5.4 bar $= 154.8'c = T_1$

Since process is isothermal, final temp. of steam $= 154.8'c = T_2$

~~Now, T_{sat} at 'p' ... $= 99.63'c$~~

Now, T_{sat} at 'p', 1 bar $= 99.63'c$

As, $T_2 > T_{sat}$ at pressure, 1 bar.

So final condition of steam is superheated.

11. $U_1 = h_1 - 100 p v_1$

~~$= 652.8 - 100 \times 5.4 \times$~~

$h_1 = h_{f_1} + x_1 h_{fg_1}$

$= 652.8 + 0.8 \times 2095.1$

$= 2331.28 \text{ kJ}$

$U_1 = 2331.28 - 100 \times 5.4 \times v_1$

$= 2331.28 - 100 \times 5.4 \times 0.8 \times v_{g_1}$

$= 2331.28 - 100 \times 5.4 \times 0.8 \times 0.34844$

~~$= 2180.77$~~

$= 2181 \text{ kJ}$

~~$h_2 = h_{f_2} + x_2 h_{fg_2}$~~

$h_2 = h_g = 2675.4 \text{ kJ}$ $\quad v_2 = v_{g_2} = 1.6938$

$U_2 = 2675.4 - 100 \times 1 \times 1.6938$

$= 2506.02 \text{ kJ}$

$du = U_2 - U_1 = 2506.02 - 2331.28$

$= 174.74 \text{ kJ}$

$h_2 = h_{sup} = [h_g + c_p(T_{sup} - T_{sat})]$

$= [2675.4 + 2.1(154.8 - 99.63)]$

$= 2791.25 \text{ kJ/kg}$

$v_2 = v_{sup}$

$\frac{v_{sup}}{T_{sup}} = \frac{v_{g_2}}{T_{sat_2}}$

$\Rightarrow v_{sup} = \frac{1.693}{372.63 K} \times 427.8 K$ $\quad$ ($154.8°C = 427.8$; $99.63°C = 372.63$)

$= 1.94 \text{ m}^3/\text{kg}$

$U_2 = h_2 - 100 p_2 v_2$

$= 2791.25 - 100 \times 1 \times 1.94$

$= 2597.25 \text{ kJ/kg}$

for 1 kg of steam.

$U_2 = 2597.25 \text{ kJ}$

$du = U_2 - U_1 = 2597.25 - 2181$

$= 416.25 \text{ kJ}$

$S_1 = S_{f_1} + x_1 S_{fg_1} = 1.890 + 0.8 \times 4.903$

$= 5.814 \text{ kJ/kg}$

$S_2 = S_{g_2} + 2.3 C_p \log \frac{T_{sup}}{}$

$= 7.360 + 2.3 \times 2.1 \times \log\left(\frac{427.8}{372.63}\right)$

$= 7.649 \text{ kJ/kg}$

$ds = S_2 - S_1 = 7.649 - 5.814$

$= 1.835 \text{ kJ/kg}$

for, m = 1kg

$ds = 1.835 \text{ kJ}$

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$\delta Q = T\,ds$

$\delta Q = 427.8 \times 1.835$

$= 785.013$ KJ

$W_{1-2} = \delta Q - \delta U$ $\quad (\because \delta Q = W_{1-2} + \delta U)$

$= 785.013 - 416.65$

$= 368.363$ KJ

Hyperbolic process ($PV = C$) :-

P_1 , P_2

$V_1 = x_1 V_{g_1}$; $V_2 = x_2 V_{g_2}$

$P_1 V_1 = P_2 V_2$

$\Rightarrow V_2 = \frac{P_1 V_1}{P_2}$

$\Rightarrow x_2 V_{g_2} = \frac{P_1 x_1 V_{g_1}}{P_2}$ (for wet condition)

$$\boxed{x_2 = \frac{P_1 x_1 V_{g_1}}{P_2 V_{g_2}}}$$

for saturation, $x_2 = 1 \Rightarrow V_2 = V_{g_2}$

for superheat,

$V_2 = V_{sup}$

$P_1 V_1 = P_2 V_{sup}$

$\Rightarrow V_{sup} = \frac{P_1 V_1}{P_2}$

for T_{sup},

$\frac{V_{sup}}{T_{sup}} = \frac{V_{g_2}}{T_{sat}}$

$W_{1-2} = 2.3 \times 100 P_1 V_1 \log\left(\frac{V_2}{V_1}\right)$

$= 230 P_1 V_1 \log\left(\frac{V_2}{V_1}\right)$

$= 230 P_1 V_1 \log\left(\frac{P_1}{P_2}\right)$ $\quad \left(\because P_1 V_1 = P_2 V_2 \Rightarrow \frac{V_2}{V_1} = \frac{P_1}{P_2}\right)$

1. Steam at a pressure of 10 bar & 0.9 dry expands to atmospheric pressure hyperbolically ($PV = C$).

Find, (i) W.D

(ii) Change in enthalpy (dh)

(iii) Change in internal energy

(iv) Heat absorbed

$C_{P_{sup\,steam}} = 2$ KJ/kg-K

$P_1 = 10$ bar $\quad T_1 = 180.0\,^\circ C$

$x_1 = 0.9$

$P_2 = 1.01325$ $\quad T_2 = 100\,^\circ C$

~~$W_{1-2} = 2.3 \times 100\, P_1 V_{g_1} \log$~~ $\quad V_1 = x_1 V_{g_1}$

i) $W_{1-2} = 2.3 \times 100 \times 10 \times 0.17487 \times \log\left(\frac{10}{1.01325}\right)$ $\quad = 0.9 \times 0.19430$ $\quad = 0.17487$ m³/kg

$= 400$ KJ/kg

~~$h_1 = 762 + 0.9 \times 2006$~~ for 1kg of steam, $W_{1-2} = 400$ KJ

ii) $h_1 = 762.6 + 0.9 \times 2013.6 = 2574.84$ KJ/kg

for 1kg , $h_1 = 2574.84$ KJ

$P_2 V_2 = P_1 V_1$

$P_2 x_2 v_{g_2} = P_1 x_1 v_{g_1}$

$x_2 = \dfrac{P_1 x_1 v_{g_1}}{P_2 v_{g_2}} = \dfrac{10 \times 0.9 \times 0.19430}{1.01325 \times 1.6730}$

$= 1.03 > 1$ ∴ it is in superheated condition.

∴ $P_2 V_2 = P_1 V_1 \Rightarrow V_2 = V_{sup} = \dfrac{P_1 V_1}{P_2} = 1.72$

$\boxed{\dfrac{V_{sup}}{T_{sup}} = \dfrac{V_{sat}}{T_{sat}}} \Rightarrow T_{sup} = \dfrac{V_{sup} \times T_{sat}}{V_{sat}}$

$= \dfrac{1.72 \times (100 + 273)}{1.673}$

$(P = 1.01325)$ (∵ $V_{sat} = V_{g_2} = 1.673$)

$= 383.5\ K$

$h_2 = h_{g_2} + C_p (T_{sup} - T_{sat})$

$= 2676 + 2.0 (383.5 - 373)$

$= 2697\ KJ/kg$ for 1 kg ; $h_2 = 2697\ KJ$

$dh = h_2 - h_1 = 2697 - 2574.84$

$= 122.16\ KJ/kg$

for 1 kg, $dh = 122.16\ KJ$

iii) $U_1 = h_1 - 100 P_1 V_1$

$U_2 = h_2 - 100 P_2 V_2$

$du = U_2 - U_1 = h_2 - 100 P_2 V_2 - h_1 + 100 P_1 V_1$

$= h_2 - 100 P_2 V_2 - h_1 + 100 P_2 V_2$ (∵ $P_1 V_1 = P_2 V_2$)

$= h_2 - h_1 = dh$

$= 122.16\ KJ$

∴ Change in internal energy = change in enthalpy.

iv) $\delta Q = du + W_{1-2}$

$= 122.16 + 400$

$= 522.16\ KJ/kg$

$\delta Q = \delta Q - W_{1-2}$

for 1 kg of steam, $W_{1-2} = 522.16\ KJ$

Isentropic process :-

→ In isentropic process there is no transfer of heat.

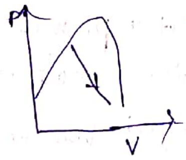
→ There is no change in entropy.

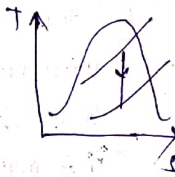
→ Work is done by expanding the steam.

$S_1 = S_2$

$S_{f_1} + x_1 S_{fg_1} = S_{f_2} + x_2 S_{fg_2}$

$S_{fg_{(2)}} = \dfrac{x h_{fg}}{T_{sat}}$





$\dfrac{V_{sup}}{T_{sup}} = \dfrac{V_{g_2}}{T_{sat_2}}$

$\delta Q = 0,\ W_{1-2} = -du$ (∵ $du = U_2 - U_1$)

$W_{1-2} = U_1 - U_2$ (for non-flow process)

According to S.F.E.E.

$\frac{1}{2} V_1^2 + g Z_1 + h_1 + Q_{1-2} = \frac{1}{2} V_2^2 + g Z_2 + h_2 + W_{1-2}$

neglecting K.E. & P.E. & isentropic process

$\frac{1}{2} V_1^2 + g Z_1 + h_1 + Q_{1-2} = \frac{1}{2} V_2^2 + g Z_2 + h_2 + W_{1-2}$ (K.E., P.E. and Q_{1-2} = 0)

$h_1 = h_2 + W_{1-2}$

$\Rightarrow W_{1-2} = h_1 - h_2$

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Note :-

1. $W = \frac{100(P_1V_1 - P_2V_2)}{n-1}$ will be used if the value of n for the steam during the expansion is given.

II. Dryness fraction of steam decreases during an adiabatic expansion. In other words the steam wetter during an adiabatic process but in cases like expansion of a steam in the nozzle of a steam turbine the steam remains in it's state of dry saturation or superheated b/z it doesn't get enough time for expansion.

1. Steam ~~at a~~ press. of 10 bar & 0.95 dry expands isentropically to a pressure of 4 bar. Determine the final dryness fraction of steam.

$x_1 = 0.95$ $P_1 = 10$ bar $S_1 = S_2$

$x_2 = ?$ $P_2 = 4$ bar

$S_{f_1} + S_{fg_1} x_1 = S_{f_2} + S_{fg_2} x_2$

$2.1387 + 0.95 \times 4.4478 = 1.7766 + x \cdot 5.1193$

$6.36411 - 1.7766 =$ ~~...~~ $x \times 5.1193$

$x \cdot 5.1193 = 4.58751$

$\Rightarrow x = 0.89$

2. Steam from an initial pressure of 7 bar & 200°C is expanded isentropically to a press. of 1 bar.

I. Calculate x_2

II. dU

III. W ...

IV. The value of W if the expansion follows pv^n.

Given, $P_1 = 7$ bar $T_1 = 200°C = 473K$ $P_2 = 1$ bar

$n = 1.13$ (wet steam)

$n = 1.135$ (dry steam)

$n = 1.3$ (super heated steam)

S.T. $T_{sat} = 165°C = 438K$

$S_{f_1} = 1.9922$ KJ/kgK

$S_{fg_1} = 4.7158$ KJ/kgK

$S_{sup_1} = 6.8865$ KJ/kgK

P_2: $S_{f_2} = 1.3026$ $S_{fg_2} = 6.0566$

i) $S_{f_1} + x S_{fg_1} = S_{f_2} + x S_{fg_2}$ $(S_{sup} = S_{f_1} + x S_{fg_1})$

$S_{sup} = S_{f_2} + x S_{fg_2}$

$\Rightarrow x = \frac{S_{sup} - S_{f_2}}{S_{fg_2}} = \frac{6.8865 - 1.3026}{6.0566}$

$= 0.92$

ii) h_{sup}: $h_1 = 2844.8$ KJ/kg

$V_{sup} = V_1 = 0.2999$ m^3/kg

$U_1 = 2844.8 - 100 \times 7 \times 0.2999$

$= 2634$ KJ/kg

$V_2 = x\, v_{g_2} = 0.92 \times 1.6940$

$= 1.55848\ m^3/kg$

$h_2 = h_{f_2} + x h_{fg_2} =$ ~~1968.216~~ 2494.82 KJ/kg

$U_2 =$ ~~1968.216~~ $2494.82 - 100 \times 1 \times 1.55848$

= ~~1812.368 KJ/kg~~

$= 2338.97$ KJ/kg

$dU = 2338.97 - 2634 = -295.025$ KJ/kg

iii) For isentropic process;

$$W_{1-2} = -dU$$
$$= -(-295.048)$$
$$= 295.048$$

iv) $P_1 V_1^n = P_2 V_2^n$

$P_1 V_{sup}^n = P_2 (x_2 v_{g_2})^n$

$$\left(\frac{V_{sup}}{x_2 v_{g_2}}\right)^n = \frac{P_2}{P_1}$$

$$n \log \frac{V_{sup}}{x_2 v_{g_2}} = \log \frac{P_2}{P_1}$$

$$\Rightarrow n = \frac{\log(P_2/P_1)}{\log\left(\frac{V_{sup}}{x_2 v_{g_2}}\right)} = \frac{\log(1/7)}{\log\left(\frac{0.2999}{0.92 \times 1.6940}\right)}$$

$$= 1.18$$

Polytropic process:–

$$W_{1-2} = \frac{100(P_1 V_1 - P_2 V_2)}{n-1}$$

1 kg of steam at a pressure of 1 bar and 0.8 dr[y]
is compressed in a cylinder to a pres. of 2 bar.
The law of compression is $PV_2^{1.2} = C$.
Find i) x_2
ii) dU
iii) S_a

Throttling process :-

- In this process no heat is supplied or rejected.
- No work is done by the expansion.
- No change in internal energy of fluid.
- The enthalpy ~~of~~ or total heat of the fluid remains constant.

Ex. 9.16
pg-259
9.17

i.e. $h_{f_1} + x_1 h_{fg_1} = h_{f_2} + x_2 h_{fg_2}$

27.10.018

STEAM BOILERS:-

* A steam generator or boiler is usally a closed vassel made of steam.

* It's func? it's transfor heat produce by the conversion of fuel to water, and ultimately to generate steam.

Classification of Steam Boiler:-

① According to the contents in the tube

Ⓐ fire tube / Smoke tube Boiler

Ⓑ Water tube Boiler

* The flames and hot gasses produce by the combusion of fuel pass through the tube which are surrounded by water.

ex:- cochran, cornish boiler.

Ⓑ Water tube Boiler:-

* The water is content inside the tube which are surrounded by flames and hot gasses.

ex:- Wilcox, La-mont boiler.

② According to the position of the funace.

Ⓐ Internally fired Boiler. [furnace is inside the boiler]

Ⓑ Externally fired Boiler. [Furnace is outside the boiler]

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(3) According to the Axis of the shell.

(A) Vertical Boilers.

(B) Horizontal Boiler.

(4) According to the no. of tubes.

(A) Single tube boiler. (only one tube)

(B) Multi tubular boiler. (more than one tube)

(5) According to the method of circulation of water and steam.

(A) Natural circulation boiler [without pump].

(B) Forced circulation boiler. [with pump]

(6) According to the use.

(A) Stationary Boiler.

* These are used in power plant and industrial process work.

(B) Mobile Boiler

These boilers are locomotive and marine boiler.

(7) According to the source of heat

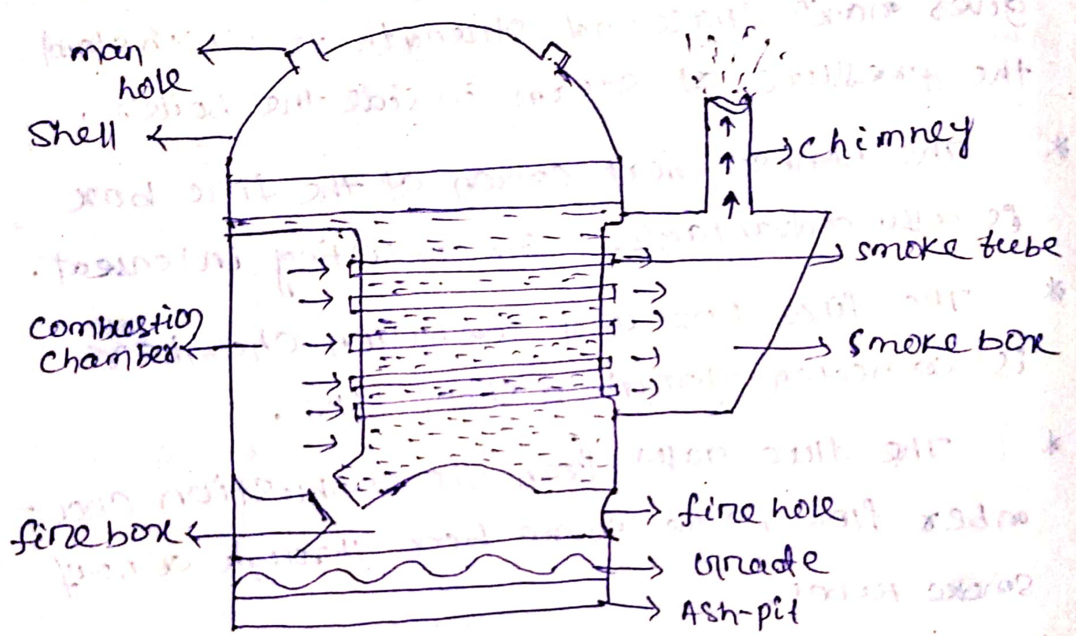
* The sources may be the combustion of solid, liquid, gasses, hot waste gases as by product of chemical processes, electrical energy, or nuclear energy etc.

COCHRAN BOILER OR VERTICAL MULTI TUBULAR BOILER

* A cochran boiler is consider to be one of the most efficient type of vertical boiler.
* The boiler consists of an external cylindrical shell and a fire box. which are hemispherical.
* The hemispherical crown of the boiler shell gives max^n space and strength to which stand the pressure of steam in side the boiler.
* The hemispherical crown of the fire box is also advantagious for resisting interheat.
* The fire box and combusion chamber is connected through a short pipe.
* The flue gases from the combustion chamber flow to the smoke box through a no. of smoke tubes.
* The gases from the smoke box pass to the atmosphear through chimney.
* The combustion chamber is lined with fire bricks on the shell side.
* A man hole near the top of crown on the shell is provided for cleaning.

* At the bottom of the fire box there is a grate (in case of coal firing) and the coal is fed through the fire hole.

* If the boiler is used for oil firing, no grate is provided but the bottom of the fire box is lined with firebricks. The oil burner is fitted at the fire hole.



Bad cock and Wilcox Boiler:-

* It is a straight tube, stationary type water tube, externally fired boiler.

water tube (100mm diameter) are incline

* The hadders are formed when view in the dir^n of tube. so the one tube is not in the space of other and the hot gases can pass properly after heating all the tubes the hadders are covered with caps.

* A mud box is provided with each down take hadder and the mud that settles down is remove.

* There is a slow moving automatic chain grated on which the coal is fed from the hopper.

* A fire bricks baffle causes hot gases to move upwards and downwards and again upward before leaving the chimney.

* The dampers are operated by a chain which passes of a pulli to the front of a boiler to regulate draught.

* Fire bricks wall are provided for a man to enter the boiler to repearing and cleaning.

* Water circulates from the drum into the hadder and through the tubes to hadder and again to the drum. Water continues to circulate like this till it is evaporated.

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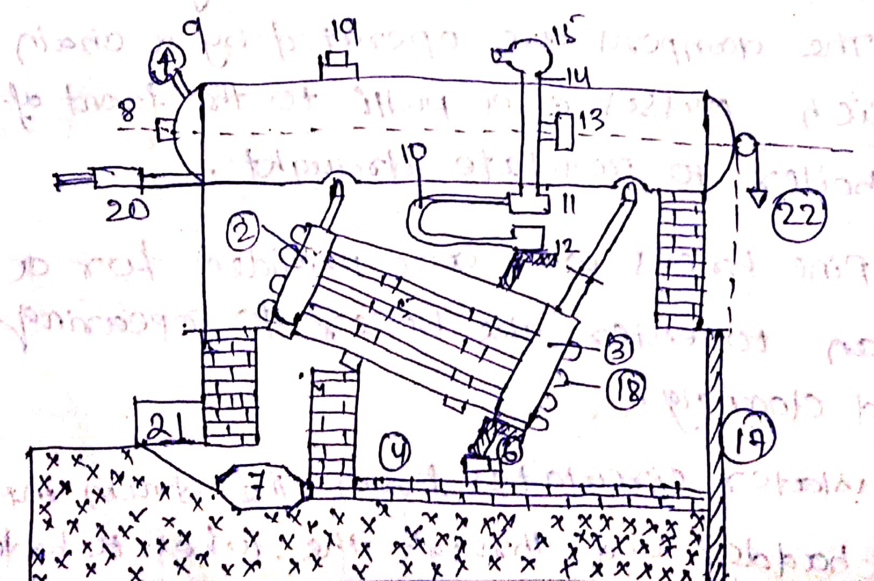
* A steam super heater consists of a large no. of steel tubes and contain two boxes, One is superheated steam box and other is saturated steam box.

* The steam generated above the water level in the drum flows in the dry pipe and through the inlet tubes into the super heated steam box. It then passes from the tubes into the saturated steam box. The steam during it passage through tubes get further heated and become super heated.

* The steam is now taken through the out-let pipe to the stop valve.



(1) Water drum :-

(2) ~~Upt~~ Uptake hadder or riser.

(3) Down tak hadder.

(4) Firebricks walls.

(5) Water tubes

(6) Mud box

(7) Grate

(8) level indicator

(9) pressure gauge

(10) Steel tubes

(11) Super heated steam box

(12) ~~Sa~~ Saturated steam box.

(13) Dry pipe

(14) outlet pipe

(15) Stop valve

(16)

(17) Dampers

(18) . Caps

(19) safty valve.

(20) feed valve

(21) hopper.

(22) Dapper chain

V

Boiler mounting

* These are the fittings mounted on the boiler for its shape and propor function

i) Water level indicator

ii) pressure Gauge

iii) Safety valve

iv) stop valve

v) Blow off cock

vi) Feed check Valve

vii) Fusible plug

i) Water level indicator :-

* Generally two no. of water level indicator are mounted on the boiler

* Its function is to show and alram, low water level and high water level in the boiler drum.

ii) Pressure Gauge :-

* A pressure gauge is used to measure instant pressure on the steam.

* Generally bourdon type or diaphgram type pressure gauges are used in steam boilers.

iii) Safety valve

* These are the devices attached to the steam chest for priventing explosion due to excessive internal pressure of the steam.

* Two no.s of safety valve are mounted on the boiler.

* The follwing '4' types of safety valve are used

a. Leaver safety valve
b. Dead weight safety valve
c. High steam and low water safety valve
d. spring loaded safety valve.

iv) Stop valve

* It is the largest valve in size placed in a boiler.

* Its function is to control flow of the steam from boiler to the main steam pipe and to shut off steam flow when required.

v) Blow off cock :-

* The blow off cock is fitted at the bottom of the boiler.
* The principle function of a blow off cock are
  a. To empty the boiler when required
  b. To discharge the mud, sediment or scale from the boiler drum.

vi) Feed check valve :-

* It's a non-return valve which ~~flows~~ works only in one direction.
* It's function is to regulate the supply of water which is pumped into the boiler by the feed pump.

vii) Fusible plugge

* It is fitted to the crown plate of the furnesh or the fire box
* Its object is to put off the fire in the furnesh of the boiler when the level of the water in the boiler falls to an uncept limit and thus avoid the explosion which may takes place due to over heating of the furnesh plate.

Boiler assosiries :-

* It is used to improve the operating condn and overal efficiency of the boiler.

* The follwing boiler assosieries as,

i. Economiser

ii. Feed water pump

iii. Superheater

iv. Separator

v. Steam trap

vi. Air free heater

vii. Ejectors.

1. Economiser :-

* It pre heats the water before it goes through the water wall tubes.

* It consist of no. of tubes and acts as a heat exchanger.

ii. Feed water pump :-

* It is a multistage Centrifugal pump.

* It pressuries water before it goes to the boiler.

iii. Superheater :-

* It is a heat exchanger use to increase the tempr of the steam.

* Generally three stages of superheater are used

I. primary superheater
II. Secondary "
III. platent "

IV. Steam separator :-

* It is used to provide dry saturated steam to the terbine.
* It's work is to separate water and mosture particle from steam.

V. Steam trap :-

* This is also an type of steam separator use to separate ~~steam~~ water from steam and Provides dry saturated steam. ~~to~~

VI. Airfree heater :-

* Boiler needs fresh air for combustion of the fuel.
* If we supply atmospheric air to the boiler then we have to supply more heat to hit up the air.
* It is a heat exchanger which pre hite the air before it goes to the boiler so, that heat supply dicreases and thus efficiency increase.

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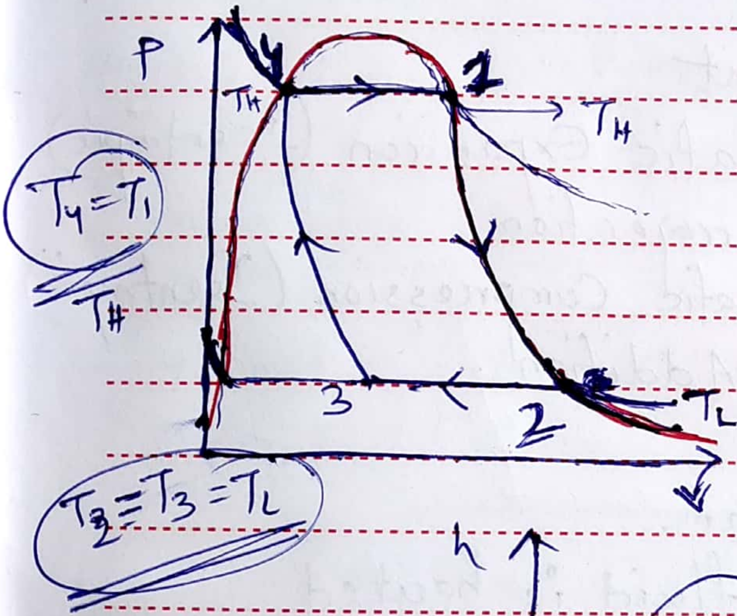
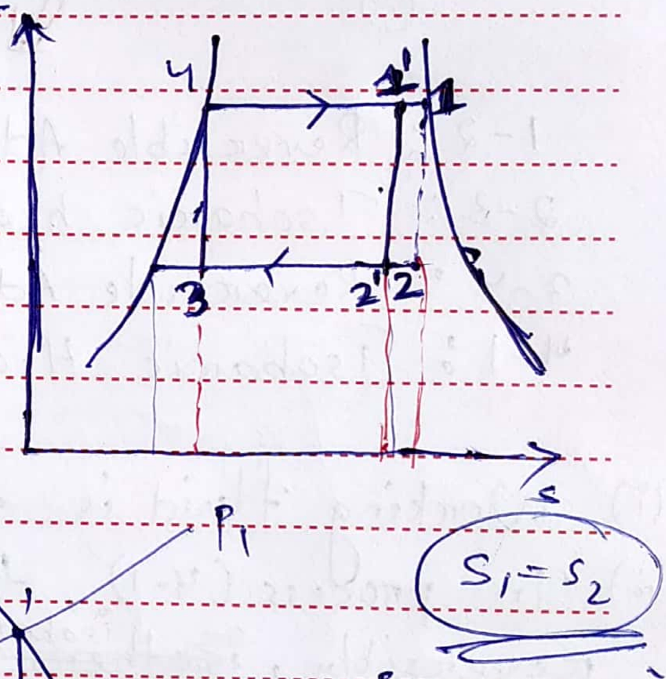
Steam Power Cycles.

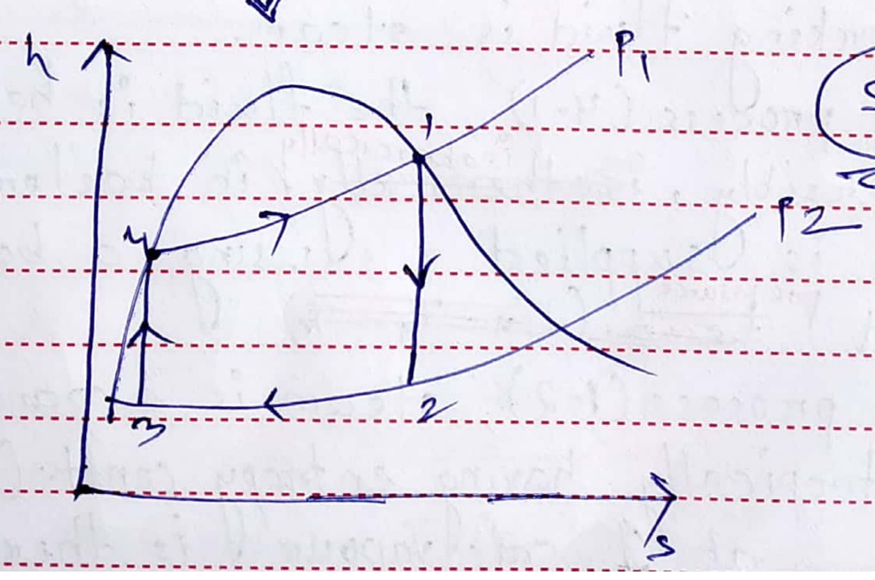
* A power cycle is defined as the cyclic process in which heat converts into work continously.

E.g. Simple steam power plant working on vapoure power cycle where working fluid is water.

* Carnot Vapour Cycle (hypothetical)







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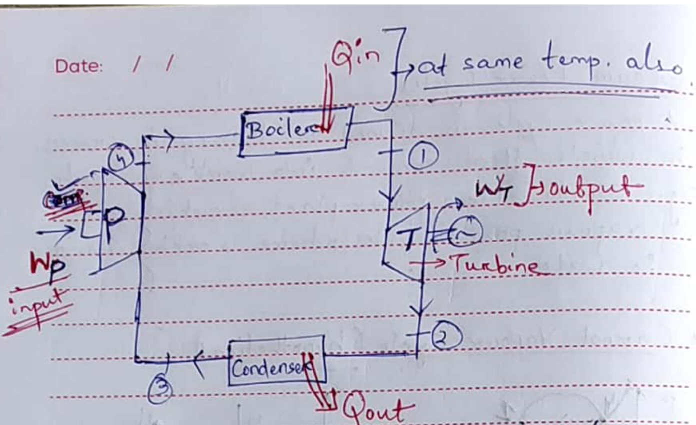
Q_{in} } at same temp. also



1-2 : Reversible Adiabatic Expansion (Isentropic)
2-3 : Isobaric heat rejection
3-4 : Reversible Adiabatic Compression (Isentropic)
4-1 : Isobaric Heat Addition

(i) Working fluid is steam.
(ii) In process (4-1), the fluid is heated reversibly, ~~isothermally~~ isobarically in boiler where heat is supplied using a boiler at a const. ~~temp.~~ pressure (~~$T_H = T_4 = T_1$~~)
(iii) In process (1-2), steam is expanded isentropically having entropy const. ($S_1 = S_2$) and at 1, sat. vapour is there. Then it ~~is~~ is expanded to 2, where it is a mixture of vapour & liquid.

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(iv) Then from 2, mixture of vapour & liquid is condensed ~~isothermally~~ isobarically (heat rejection) and reaches point 3.
(v) Finally, from point 3, it is compressed isentropically by a ~~compressor~~ pump in order to reach its original state which is sat. liquid.

+ Efficiency $= \frac{W_{net}}{Q_{supplied}} = \frac{W_T - W_P}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}}$

From T-s diagram,

→ heat supplied, $Q_{in} = T_H (S_1 - S_4)$, ($Q = T\Delta S$)
but since, $S_1 = S_2$ & $S_3 = S_4$

⇒ $Q_{in} = T_H (S_2 - S_3)$

→ heat rejected, $Q_{out} = T_L (S_2 - S_3)$

Now for cycle, $\Sigma Q = \Sigma W$ (First law of T.D.)

⇒ $W_{net} = T_H (S_2 - S_3) - T_L (S_2 - S_3)$
$= (T_H - T_L)(S_2 - S_3)$

→ $W_T - W_P$

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$\Rightarrow \eta = \frac{W_{net}}{Q_{in}} = \frac{(T_H - T_L)(S_2 - S_1)}{T_H (S_2 - S_1)}$

$\Rightarrow \boxed{\eta = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H} = 1 - \frac{Q_{out}}{Q_{in}}}$

From h-s diagram (Mollier can be used to find out required values)

We can write,

$h_1 + W_T = h_2$ } → for (1→2)

$\Rightarrow W_T = W_{out} = h_1 - h_2$

Similarly,

$Q_{out} = h_2 - h_3$

$W_P = W_{in} = h_4 - h_3$

$\Rightarrow W_{net} = W_T - W_P = (h_1 - h_2) - (h_4 - h_3)$

$\Rightarrow Q_{in} = (h_1 - h_4)$.

$\Rightarrow \boxed{\eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}}$

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* So, now if, W_{in} is very small compared to W_{out} i.e. W_T, then W_{in} or W_P can be neglected.

$\Rightarrow \boxed{\eta = \frac{(h_1 - h_2)}{h_1 - h_4}}$ $(W_T >>> W_C)$

~~Rankine Cycle~~

→ ~~It is a theoretical cycle.~~

→ Important terms related to Steam Power Cycle.

1) Thermal efficiency $(\eta) = \frac{W_{net}}{Q_{in}}$

2) Back Work Ratio: It is the fraction of the work produced by turbine that is consumed by the compressor/pump.

$\boxed{BWR = \frac{W_P}{W_T}}$

3) Steam Rate (Specific Steam Consumption) (SSC)

↳ mass of steam required to generate 1 kW-h (3600 kJ) of power.

$\boxed{SSC = \frac{3600 \,(kJ/kW\text{-}h)}{W_{net}\,(kJ/kg)}}$ kg/kW-h

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4) Heat Rate → amount of energy (heat) required to produce 1 kW-h of power.

$$HR = \frac{3600 \text{ kJ/kWh}}{\eta_{th}}$$

Limitation of Carnot Vapour Cycle.

1) Compressor cannot work by water.
2) Wet steam can't be handled by pump.
3) It is impossible to locate point 3 as limit of condensation is not known.

Rankine Cycle.

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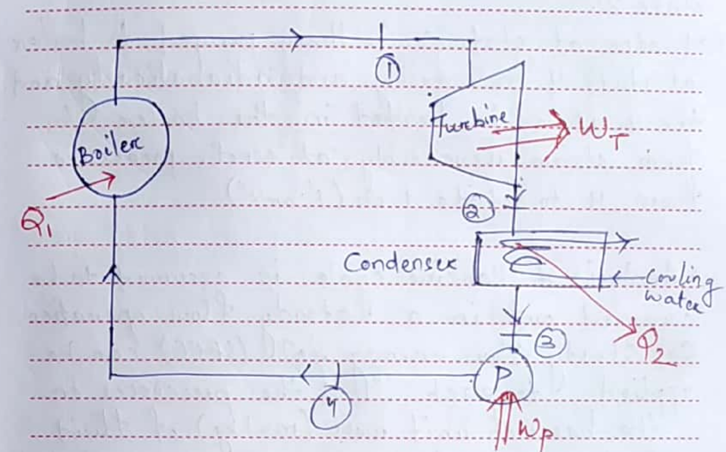
→ It is an ideal cycle (i.e processes involved all are reversible in nature)



→ For any given pressure, the steam approaching the turbine may be dry saturated (state 1), wet (state 1') or superheated state (state 1''), but the fluid approaching the pump in each case, is saturated liquid (state 3).

→ Steam expands reversibly and adiabatically in the turbine from state 1 to 2 (or 1' to 2' or 1'' to 2''), the steam

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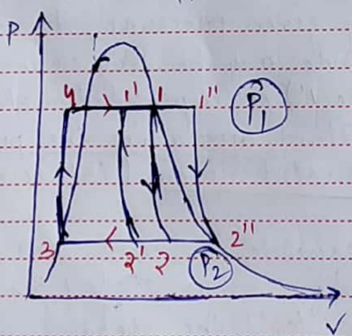
leaving the turbine condenses to water in the condenser reversibly at const. pressure from state 2 (or 2' or 2'') to state 3.

→ Water at state 3 is then pumped to boiler at state 4 reversibly and adiabatically and the water is heated in the boiler to form steam reversibly at const. pressure from 4 to state 1 or (1' or 1'')

→ Analysis of Rankine cycle is assumed to be carried out in a steady flow operation. So, Steady flow energy eqn (SFEE) can be applied to each of the processes on the basis of unit mass (m=1 kg) of fluid and changes in K.E & P.E can be neglected.



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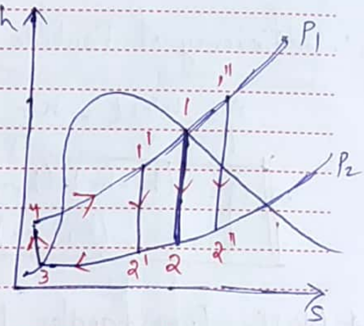

For 1kg of fluid

S.F.E.E (for boiler)

$h_4 + Q_1 = h_1$

$\Rightarrow \boxed{Q_1 = h_1 - h_4}$ kJ/kg ——— (i)

S.F.E.E for turbine

$h_1 = W_T + h_2$

$\Rightarrow \boxed{W_T = h_1 - h_2}$ kJ/kg ——— (ii)

S.F.E.E for condenser

$h_2 = Q_2 + h_3$

$\Rightarrow \boxed{Q_2 = h_2 - h_3}$ ——— (iii) kJ/kg

S.F.E.E for Pump,

$h_3 + W_p = h_4$

$\Rightarrow \boxed{W_p = h_4 - h_3}$ ——— (iv) kJ/kg.

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∴ efficiency of Rankine Cycle

$$\eta = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1}$$

$$\Rightarrow \eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

* NOTE: Pump handles liquid water which is incompressible i.e its density, specific volm undergoes very little change with increase in pressure.
So in (3-4) i.e reversible adiabatic compression specific volm doesn't change considerably.

So using $T\,ds^{\,0} = dh - v\,dp$ (for 3-4) [ds → isentropic]

$\Rightarrow dh = v\,dp$

$\Rightarrow h_4 - h_3 = v_3 (P_1 - P_2)$

if v is in m^3/kg & P_1 & P_2 in bar,

$\Rightarrow h_4 - h_3 = v_3 (P_1 - P_2) \times 10^2$ kJ/kg

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* Work Ratio ⇒ It is the ratio of net work output to positive work output.

∴ Work Ratio = $W_{net}/W_T = (W_T - W_P)/W_T$

* pump work is usually quite small compared to turbine work.
So neglecting pump work i.e $h_4 \simeq h_3$,

$$\eta = \frac{(h_1 - h_2)}{h_1 - h_4}$$

* Steam Rate = $\frac{3600}{W_T - W_P}$ kJ/kW-h

* Heat Rate = $\frac{3600 \times Q_1}{(W_T - W_P)} = \frac{3600}{\eta_{cycle}}$ kJ/kW-h

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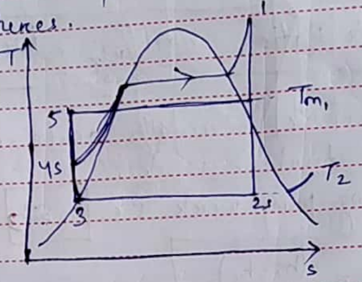
Mean temp. of heat addition

In the Rankine cycle, heat is added reversibly at a const. pressure but at infinite temperatures.



If T_{m_1} is the mean temp. of heat addition, so that area under 4s & 1 is equal to area under 5&6.

$$\Rightarrow Q_1 = h_1 - h_{4s} = T_{m_1}(s_1 - s_{4s})$$

$$\Rightarrow \boxed{T_{m_1} = \frac{h_1 - h_{4s}}{s_1 - s_{4s}}}$$

$$\Rightarrow Q_2 = h_{2s} - h_3 = T_2(s_1 - s_{4s}) \quad \left[\because s_1 = s_{2s},\ s_3 = s_{4s}\right]$$

$$\eta_{Rankine} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(s_1 - s_{4s})}{T_{m_1}(s_1 - s_{4s})}$$

$$\Rightarrow \boxed{\eta_{Rankine} = 1 - (T_2/T_{m_1})}$$

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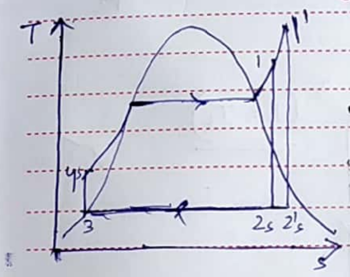
T_2 = temp. of heat rejection

$\therefore$ So lower the T_2, for a given T_{m_1} the higher will be the efficiency of cycle.

Note lowest value of T_2 can be surrounding temp.

if T_2 being fixed, then $\boxed{\eta_{Rankine}\uparrow = \uparrow f(T_{m_1})}$ only

⇒ Effect of increasing the initial temp. at const. press.



- when initial temp. changes from T_1 to T_1', T_{m_1} that was in 4s & 1 now increases & it is $T_{m_1'}$ where it is area under 4s & 1'.

As T_{m_1} increases to $T_{m_1'}$, so efficiency will increase.

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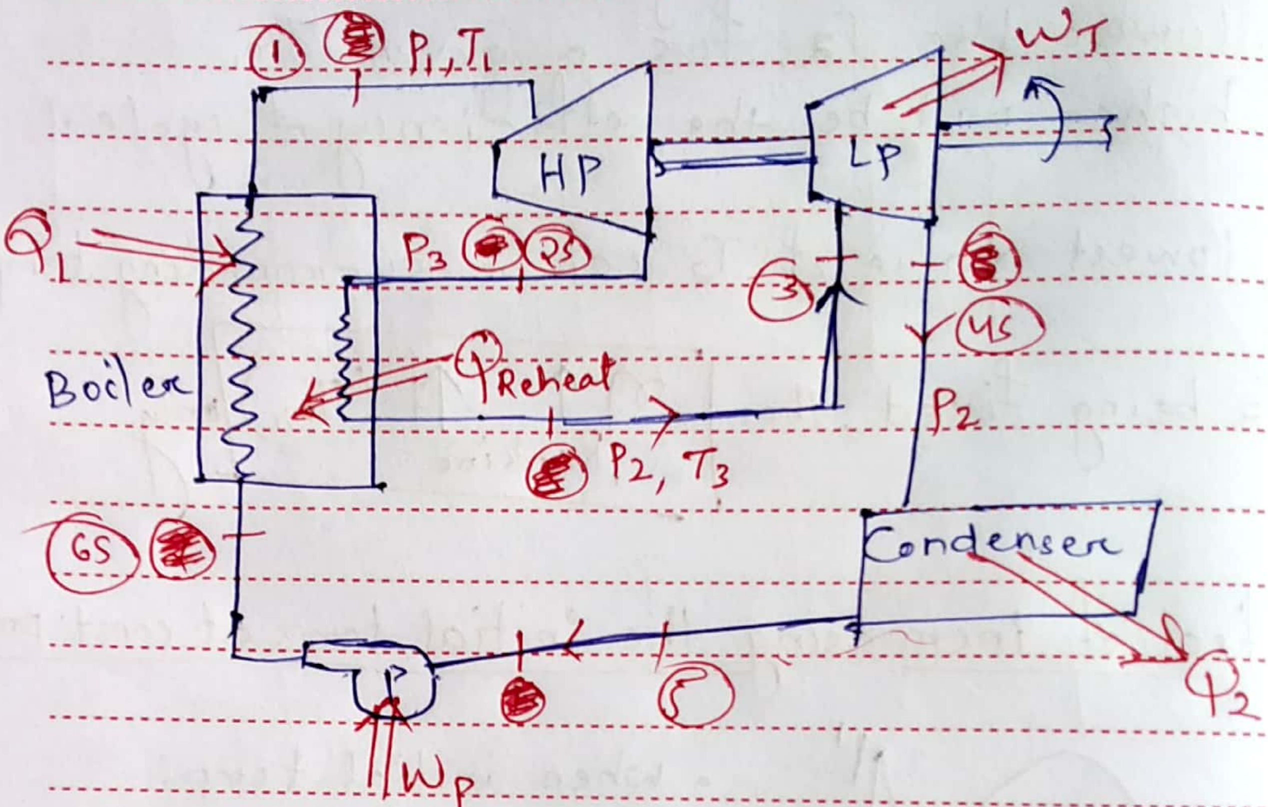
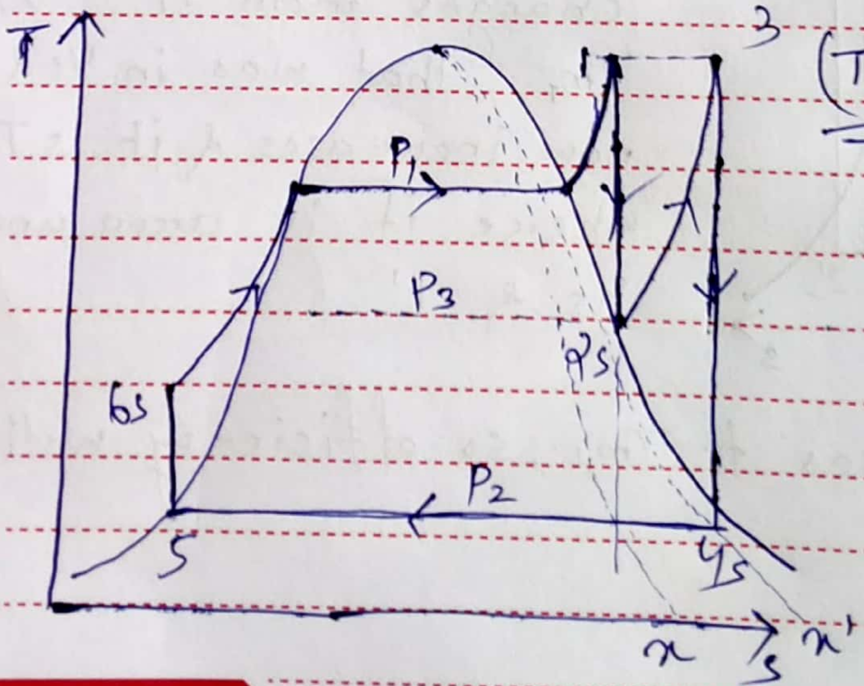
Reheat Cycle

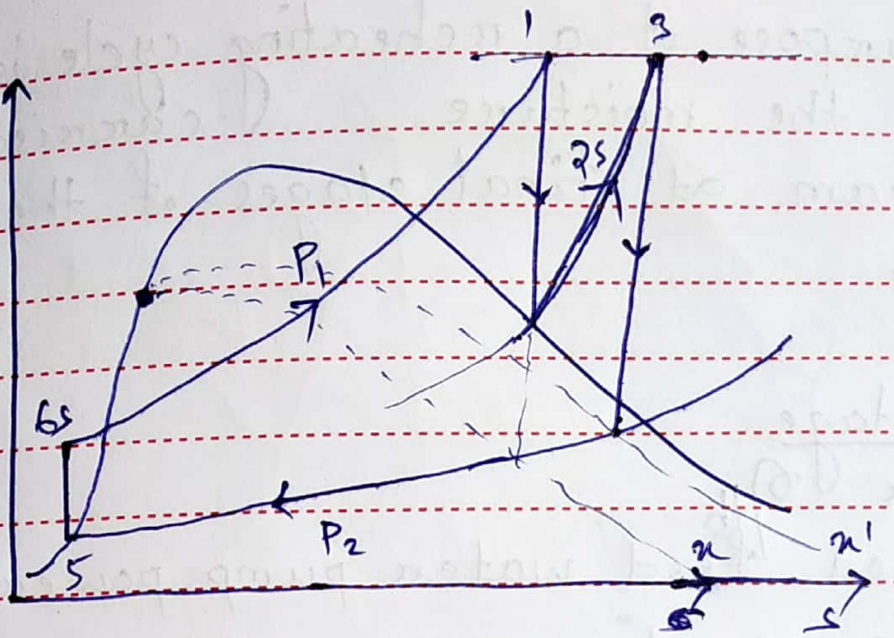




$(T_1 = T_3)$

$x' > x$

Steam quality improved



→ In the reheat cycle, expansion of steam from initial state 1 to condenser pressure(P_2) is carried out in two or more steps, depending upon the no. of reheats used.

→ In the first step, steam expands in High Pressure (HP) turbine from initial state to approximately sat. vapour. (Process 1-2s).

→ The steam is then reheated at const. pressure in the boiler (Process 2s-3) and remaining expansion (Process 3-4s) is carried out in Low Pressure (L.P.) turbine.

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→ The purpose of a reheating cycle is to remove the moisture carried by the steam at final stages of the expansion process.

→ Advantage :

1) higher η_{th}
2) Reduced feed water pump power
3) Smaller condenser
4) Smaller Boiler
5) Long life of turbine.

→ $Q_1 = (h_1 - h_{6s}) + (h_3 - h_{2s})$
$Q_2 = (h_{4s} - h_5)$

$W_T = (h_1 - h_{2s}) + (h_3 - h_{4s})$
$W_P = (h_{6s} - h_5)$

$\therefore \eta = \frac{W_T - W_P}{Q_1} = \frac{(h_1 - h_{2s} + h_3 - h_{4s}) - (h_{6s} - h_5)}{(h_1 - h_{6s}) + (h_3 - h_{2s})}$

$\therefore$ Steam Rate $= \frac{3600}{(h_1 - h_{2s} + h_3 - h_{4s}) - (h_{6s} - h_5)}$ kg/kw-h

→ h is in kJ/kg.

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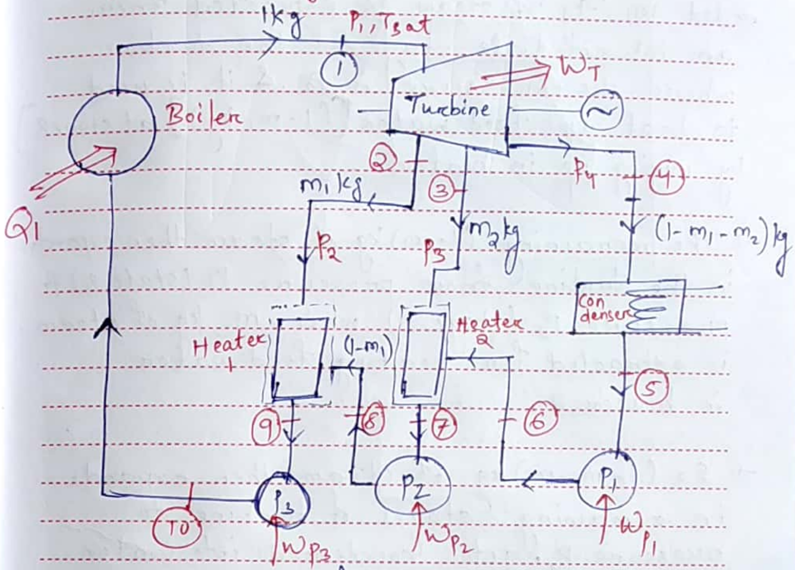
Regenerative Cycle



→ Regeneration refers to a method where the certain quantity of heat abstracted from the steam is utilized to heat the water. The regeneration process occurs b/w stages of turbine and pump respectively.

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→ For every kg of steam entering the turbine, let m_1 kg of steam be extracted from an intermediate stage of the turbine, where the pressure is P_2 & it is used to heat up feed water [$(1-m_1$ kg$)$ at stage 8] by mixing up in heater-1.

→ The remaining $(1-m_1)$ kg of steam then expands in the turbine from pressure P_2 (state 2) to pressure P_3 (stage 3) when m_2 kg of steam is extracted for heating feed water in heater 2.

→ So $(1-m_1-m_2)$ kg of steam then expands in remaining stages of turbine to pressure P_4, gets condensed into water in condenser & pumped to heater 2, where it mixes with m_2 kg of steam extracted at pressure P_3.

→ Then $(1-m_1)$ kg of water is pumped to heater 1, where it mixes with m_1 kg of steam extracted to pressure P_2.

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→ The resulting 1 kg of steam is then pumped to the boiler where from an external source is supplied.

→ Heaters 1 & 2 thus operate at Pressure P_2 & P_3 respectively.

⇒

$W_T = 1(h_1-h_2) + (1-m_1)(h_2-h_3) + (1-m_1-m_2)(h_3-h_4)$

$W_P = W_{P_1} + W_{P_2} + W_{P_3}$

$= (1-m_1-m_2)(h_6-h_5) + (1-m_1)(h_8-h_7) + 1(h_{10}-h_9)$

$Q_1 = 1(h_1-h_{10})$, $Q_2 = (1-m_1-m_2)(h_4-h_5)$

$\therefore \eta = \dfrac{Q_1-Q_2}{Q_1} = \dfrac{W_T-W_P}{Q_1}$

$\therefore$ Steam Rate $= \dfrac{3600}{W_T-W_P}$

⇒ $(T_{m_1})_{\text{with regeneration}} = \dfrac{h_1-h_{10}}{s_1-s_{10}}$

⇒ $(T_{m_1})_{\text{without regeneration}} = \dfrac{h_1-h_6}{s_1-s_6}$

$\therefore (T_{m_1})_{\text{regeneration}} > (T_{m_1})_{\text{w/o regeneration}}$

⇒ $\eta_{\text{reg.}} > \eta_{\text{w/o regeneration}}$

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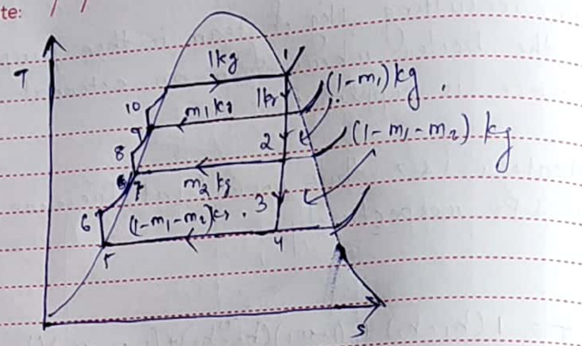

Writing energy balance for heater 01: ($E_{in} = E_{out}$)

$\Rightarrow m_1 h_2 + (1-m_1) h_8 = 1 \times h_9$

$$\Rightarrow \boxed{m_1 = \frac{h_9 - h_8}{h_2 - h_8}}$$

again for energy balance for heater 2

$$m_2 h_3 + (1 - m_1 - m_2) h_6 = (1 - m_1) h_7$$

$$\Rightarrow \boxed{m_2 = (1 - m_1) \frac{h_7 - h_6}{h_3 - h_6}}$$

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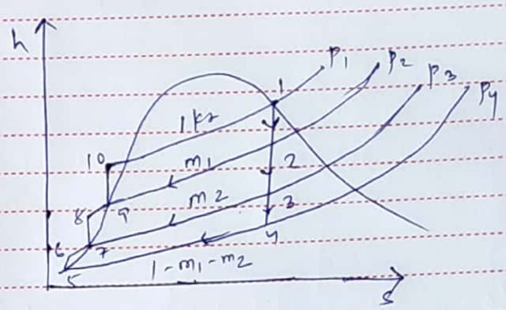

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Heat Transfer

Difference b/w heat & temperature

1) Temperature is ~~the~~ a measure of the amount of energy possessed by molecules of a substance. It manifests itself as degree of hotness.

2) Heat, on the hand, is energy in transit. Spontaneously, heat flows from a hotter body to a colder one.

Difference b/w Thermodynamics & Heat Transfer

Thermodynamics	Heat Transfer
It tells us	It tells us
1) how much heat is transferred (δQ)	1) how δQ is transferred
2) how much work is done (δW)	2) at what rate δQ is transferred
3) final state of system	3) temp. distribution inside the body.

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Modes of heat transfer

1) Conduction, 2) Convection, 3) Radiation.

* The transmission of energy from one region to another as a result of temp. gradient, is called as Heat Transfer.

I] Conduction

* Conduction is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance.

* In solids, heat is conducted by following two mechanisms.

(i) By Lattice vibration.

(ii) By transport of free e's → (Metals & other good electric conductors)

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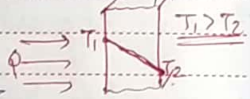
→ In case of gases the kinetic energy of a molecule is a function of temp. These molecules are in a continous random motion exchanging energy & momentum.

Fourier's Law of Conduction.

→ It is an emperical law based on observation and states as follows
" The rate of flow of heat through a simple homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temp with respect to the length of the path of heat flow."



Mathematically, $Q \propto A \cdot \frac{dT}{dx}$

where, Q = heat flow through a body per unit time (watt)

(m^2) A = Surface area of heat flow ($\perp^r$ to heat flow)

dT = Temp. difference along thickness 'dx'

dx = Thickness of body in the direction of heat flow.

($\frac{dT}{dx}$ → temp. gradient)

So, $Q = -K \cdot A \cdot \frac{dT}{dx}$

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K = Const. of proportionality and is known as thermal conductivity of the body

Note: The negative sign is to take care of the decreasing temp. along with dir^n or increasing thickness.

* The temp gradient dT/dx is always -ve along dir^n of heat flow.

Assumptions regarding law:

1. Conduction of heat takes place under steady state conduction.
2. The heat flow is unidirectional.
3. The temp. gradient is constant and temp. profile is linear.
4. There is no internal heat generation.
5. The bounding surfaces are isothermal in character.
6. The material is homogeneous & isotropic.

emami DOUBLE BULL CEMENT
Mazbooti Ummeed Se Zyada

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Essential Features of Fourier's law

1. It is applicable to all matter (solid, liquid & gas)
2. It is based on experimental evidence and cannot be derived from principles.
3. It is a vector expression indicating that heat flow is in the dirn of decreasing temp. & is normal to an isotherm.
4. It helps to define thermal conductivity (k) of medium through which heat is conducted.

Thermal Conductivity of materials

$$K = \frac{Q}{A}\frac{dx}{dT}$$

The value of K = 1 when Q = 1, A = 1 & $\frac{dx}{dT} = 1$
unit → W/mK or W/m °c

* Thermal conductivity of a material is defined as the amount of energy conducted through a body of unit area & unit thickness in unit time when difference in temp. b/w the faces causing heat flow is unit temp. difference.

* It is a transport property.

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* Thermal conductivity depends upon
(1) Material structure
(2) Moisture content
(3) Density of material
(4) Pressure & temperature

Material	(W/mK) Thermal Conductivity
Silver	410
Copper	385
Aluminium	225
Cast Iron	55-65
Steel	20-45
Concrete	1.20
Glass (window)	0.75
Asbestos Sheet	0.17
Glass wool	0.03
Water	0.55-0.7
Freons	0.0083

* K for pure metals is the highest. It decreases with increase in impurity.

$K_{metal} > K_{alloy} > K_{non\text{-}metal}$

* $K_{solid} > K_{liquid} > K_{gas}$

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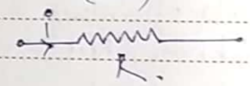
* k of metal mostly decreases with increase in temp.
* In most of liquids, the value of k tends to decrease with temp. due to decrease in density with increase in temp.

* In case of gases the value of k increases with increase in temp.

* $Q = -KA\frac{dT}{dx}$

$$\Rightarrow Q = -\frac{dT}{\left(\frac{dx}{KA}\right)} = \frac{\text{Temp. difference}}{\left(\frac{dx}{KA}\right)}$$

* As ohm's law,



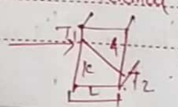
$I = V/R$ R → resistance

Doing electrical analogy.

Heat flow rate (Q) = $\frac{\text{Temp difference}}{(dx/KA)}$

$\Rightarrow \frac{dx}{KA} \rightarrow$ Thermal Resistance (R_{th})

or Conductive Thermal Resistance $\left(\frac{L}{KA}\right)$



$\therefore Q = \frac{\Delta T}{R_{th}} = \frac{\Delta T}{(L/KA)}$

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Convection

* Convection is the transfer of heat within a fluid by mixing of one portion of fluid with another.
* Convection is only possible in a fluid medium and is directly linked with the transport of medium itself.

→ Free or Natural Convection

It occurs when fluid circulates by virtue of natural differences in densities of hot & cold fluids; denser portions of fluid move downward because of greater force of gravity.

→ Forced Convection

When the work is done to blow or pump the fluid, it is said to be forced convection.

* Here, heat flow depends on properties of fluid and is independent of the properties of material of the surface.

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Newton's law of Cooling

* The rate eqⁿ for convective heat transfer b/w a surface and an adjacent fluid is prescribed by this law,

$$Q = hA(T_s - T_f)$$

where, Q = Rate of convective heat transfer
A = Area exposed to heat transfer
T_s = Surface temp.
T_f = fluid temp.
h = Coefficient of convective heat transfer

unit of h, $h = \frac{Q}{A(T_s - T_f)}$ $\left(W/m^2 k \text{ or } W/m^2 {}^\circ c \right)$

→ Coefficient of convective heat transfer 'h' is defined as the amount of heat transmitted for a unit temp. difference b/w fluid and unit area of surface in unit time.

→ $Q = \frac{\Delta T}{hA}$ → Convective thermal resistance $= \frac{1}{hA}$

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h depends upon

i) thermodynamic & transport properties (e.g. viscosity, density, specific heat etc.)

ii) Nature of fluid flow

iii) Geometry of surface.

iv) Prevailing thermal conditions

Radiation

→ Radiation is the transfer of heat through space or matter by means other than conduction or convection.

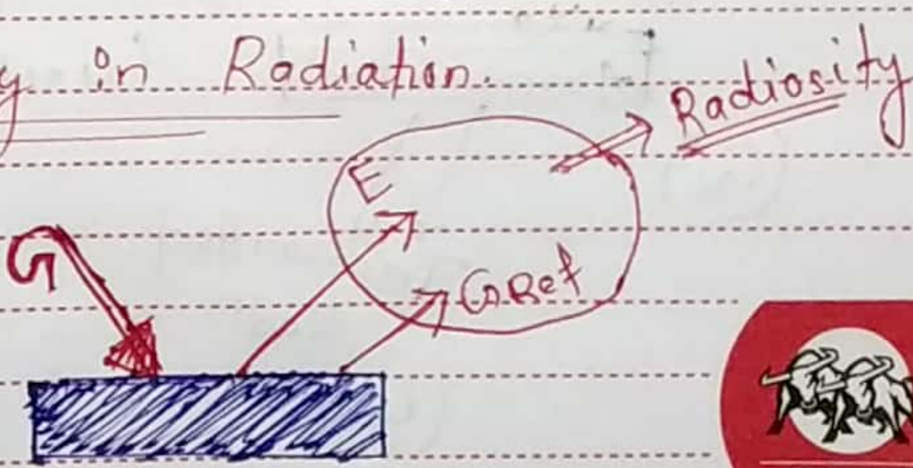
→ Properties of Radiation.

1) It doesn't require the presence of a material medium for its transmission.

2) Radiant heat can be reflected from the surfaces and obeys the ordinary laws of reflection.

3) It travels with velocity of light.

Terminology in Radiation.



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Radiation Fluxes:

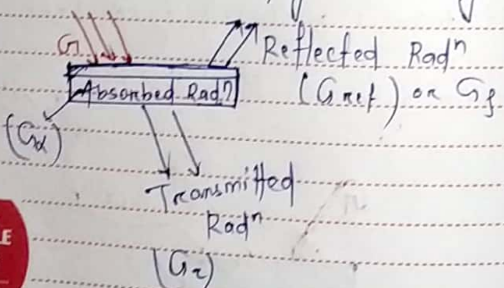
(1) Emissive Power (E) W/m^2
Rate at which radiation is emitted from surface per unit area of surface.

(2) Irradiation (G) W/m^2
Rate at which radiation is incident upon a surface per unit area of the surface.

(3) Radiosity (J) W/m^2
Rate at which radiation leaves the surface per unit area of the surface.

$\Rightarrow$ $\boxed{J = E + G_{Ref}}$ G_{ref} = Reflected fraction of G.

* If incident radiation impinges in a body



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$\Rightarrow G = G_\alpha + G_\tau + G_\rho$
dividing G on both sides

$\Rightarrow \frac{G_\alpha}{G} + \frac{G_\tau}{G} + \frac{G_\rho}{G} = 1$

$\Rightarrow \boxed{\alpha + \tau + \rho = 1}$ —— (i)

1) Reflectivity (ρ)
↳ fraction of irradiation reflected
$\rho = \frac{G_\rho}{G}$

$\Rightarrow \boxed{J = E + \rho G}$ ($\because \rho G = G_\rho$)

2) Absorptivity (α)
↳ fraction of irradiation absorbed
$\alpha = G_\alpha / G$

3) Transmissivity (τ)
↳ fraction of irradiation transmitted
$\tau = \frac{G_\tau}{G}$.

$\therefore$ $\boxed{0 \leq \alpha, \rho, \tau \leq 1}$ —— (ii)

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Different Type of Surfaces.

1) On the basis of τ.
if $\tau = 0$; → $\alpha + \rho = 1$ → Opaque Surface
$\tau = 1$; $\alpha + \rho = 0$ → perfectly transperent or Diathermanous.

2) On the basis of ρ
if $\rho = 0$; $\alpha + \tau = 1$ → Non-reflecting Surface
$\rho = 1$; $\alpha + \tau = 0$ → perfect reflector
↳ white body

3) On the basis of α
if $\alpha = 0$; $\rho + \tau = 1$ → Non-absorbing surface
if $\alpha = 1$; $\rho + \tau = 0$ → perfectly absorbing surface.

Concept of Black Body

→ A black body is an object that absorbs all the radiant energy reaching its surface.

→ For a black body → $\alpha = 1$, $\rho = 0$, $\tau = 0$.

→ No actual body is perfectly black.

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Properties of black body.

1) It absorbs all the incident radiation falling on it.
2) It emits max^m amount of thermal radiations at all wavelengths at any temp.
3) It is a diffuse emitter.

1) Stefan - Boltzman's Law

The law states that the emissive power of a black body is directly proportional to fourth power of its absolute temp.

i.e

$$E_b = \sigma T^4$$

σ → Stefan-boltzman Constant

$\sigma = 5.67 \times 10^{-8}\ W/m^2 K^4$

For a real body, formula for emissive power

$$E = \alpha E_b$$

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2) Kirchoff's Law

The law states that at any temp. the ratio of total emissive power (E) to the total absorptivity α is a const for all substances which are in thermal eq^m with their environment.

* Emissivity (ϵ) $= \frac{E}{E_b}$ & $(0 \leq \epsilon \leq 1)$.

* Kirchof's law also states that emissivity of a body is equal to its absorptivity when the body is in thermal eq^m with its surroundings.

i.e. $\epsilon = \alpha$

3) Planck's Law

$$(E_\lambda)_b = \frac{2\pi h c^2}{\lambda^5\left[e^{\frac{hc}{\lambda K T}} - 1\right]} = \frac{C_1}{\lambda^5\left[e^{\frac{C_2}{\lambda T}} - 1\right]}$$

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Where

$(E_\lambda)_b$ = Monochromatic emissive power of black body
c = velocity of light $= 3\times10^8$ m/s
λ = wavelength, in μm
$h = 6.625 \times 10^{-34}$ J·s.
K = Boltzmann's Const $= 1.3805 \times 10^{-23}$ J/K
T = Absolute Temp., (K)

$C_1 = 2\pi h c^2 = 3.742 \times 10^8$ W·$\mu m^4/m^2$
$C_2 = \frac{hc}{K} = 1.4388 \times 10^4$ μmK

→ $(E_\lambda)_b$ is defined as energy emitted by the black surface in all directions at a given wavelength λ per unit wavelength interval around λ.

4) Wien's Displacement Law

It establishes a relationship b/w temp. of a black body and wavelength at which the max^m value of monochromatic emissive power occurs.

It states that

$\lambda_{max} \times T$ = Const. $= 2897.8$ μm·K

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