4024 THERMAL ENGINEERING

MODULE 3

SALEEM N
LECTURER IN ME, KGPTC

MODULE III

- **3.1.0 Appreciate the testing of IC Engines**
- 3.1.1 State the importance of performance testing of I.C. Engines
- 3.1.2 Define Indicated power, Brake Power, Friction Power, and Mechanical Efficiency
- 3.1.3 Define Indicated Thermal efficiency, Brake Thermal efficiency, Relative efficiency
- 3.1.4 Define Total fuel consumption & Specific Fuel Consumption.
- 3.1.5 Explain the Morse test.
- 3.1.6 Solve Simple problems for 3.1.2 to 3.1.5
- 3.1.7 Explain Heat balance sheet
- 3.1.8 Solve Simple problems for 3.1.7
- **3.2.0 Steam and its Properties**
- 3.2.1 Understand the formation of steam and steam properties
- 3.2.2 List the uses of steam
- 3.2.3 Explain the formation of steam at constant pressure with a graph indicating the effect of
- pressure and temperature
- 3.2.4 Distinguish between wet steam, dry steam and superheated steam

- 3.2.5 Compute the enthalpy of wet, dry and super heated steam at the given pressure and state using
- steam tables
- 3.2.6 Compute the heat required to produce steam at given pressure and state from feed water.
- 3.2.7 Construct T-S and Mollier charts and represent various pressures in them
- 3.2.8 Determine the condition of steam, enthalpy, entropy specific volume of steam using mollier
- chart.
- 3.2.9 Understand the different parts and the working and of Steam Engine
- 3.2.10 Explain the working of a double acting Steam Engine with simple line sketch
- 3.2.11 Understand the various thermodynamic vapour cycles.
- **3.3.0 Recognize the use and application of Steam Nozzles**
- 3.3.1 State the functions of a steam Nozzle
- 3.3.2 Explain the convergent nozzles and convergent – divergent nozzles
- 3.3.3 Derive the expression of velocity of steam leaving a nozzle
- 3.3.4 Compute the velocity of steam leaving a nozzle with the help of Mollier chart

TESTING OF IC ENGINES

IMPORTANCE OF PERFORMANCE TESTING OF I.C. ENGINES

- The testing of I.C. Engines is the process of assessing the performance and operation of the engine in the efficient manner.
- There are various parameters which can be measured for testing of I.C. Engines.
- The testing of the engine is necessary for understanding the efficient operation of the engine and the engine components.
- The testing of the engine provides improvement in the performance of the engine by increasing the efficiency and fuel economy of the engine.
- The continuous testing of engine can maintain fuel efficient operation of the engine and help in diagnosis of the failures of parts or components.

INDICATED MEAN EFFECTIVE PRESSURE

- It is the hypothetical pressure of an engine which is acting on the piston throughout the power stroke.
- This is obtained from an indicator diagram (P-V diagram) obtained from an engine indicator.
- $$P_m = h \times S$$
- Where, h = Mean height of the indicator diagram in meter.
- S = Spring scale of the indicator spring in kPa/m
- $$h = \frac{Area\ of\ indicator\ diagram\ in\ m^2}{Length\ of\ indicator\ diagram\ in\ m}$$

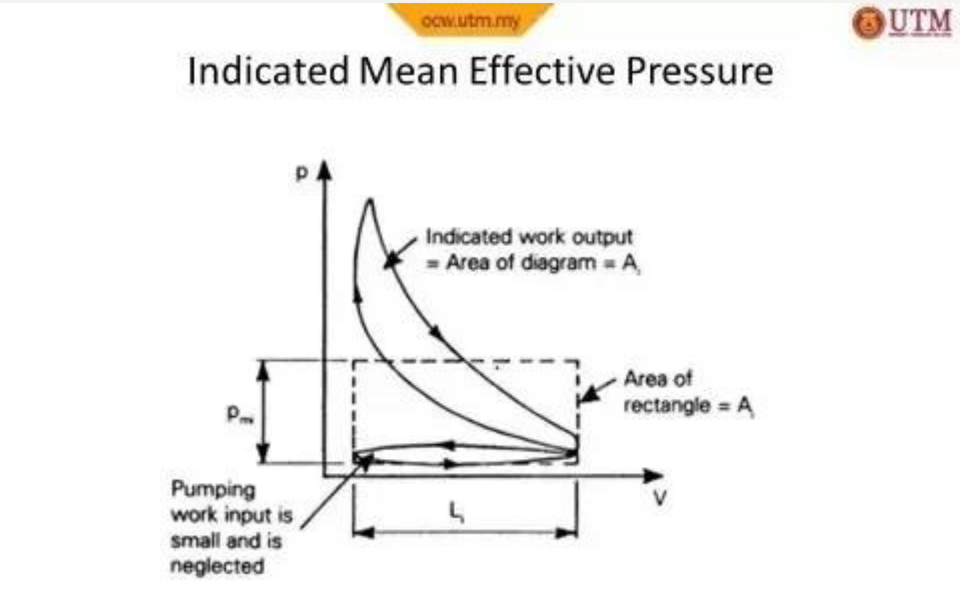


Figure 1.3. Indicator Diagram

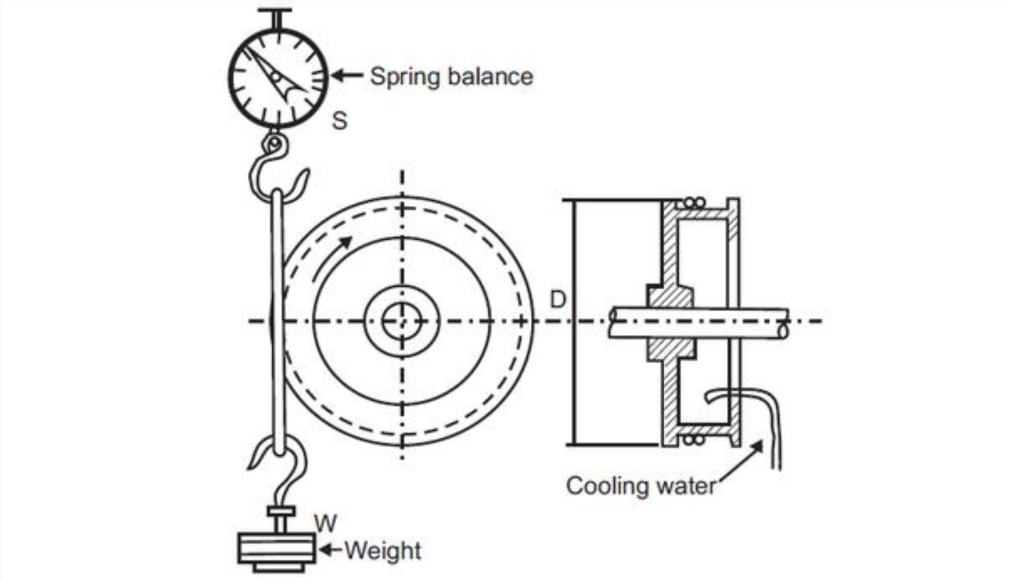
INDICATED POWER (IP)

- It is the actual power developed inside an engine cylinder during its operation.
- $$IP = \frac{P_m L A n}{60}$$
- Where,
- P_m = Indicated mean effective pressure in kPa.
- L = Stroke length in meter
- A = Area of the piston in m^2
- n = Number of power strokes per minute.
- For 2-Stroke engine, n = N
- For 4-Stroke engine, n = N/2
- Where,
- N = rpm of the engine.
- For a multi-cylinder engine,
- $$IP = \frac{P_m L A n K}{60}$$
- Where,
- K = Number of cylinders.

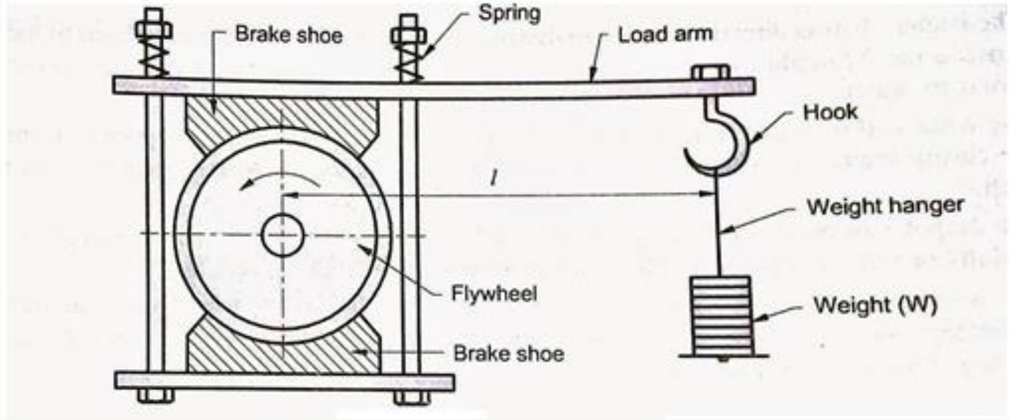
BRAKE POWER (BP)

- The useful power available at the output shaft of an engine is known as brake power.
- $$BP = \frac{2\pi NT}{60}$$
- Where,
- N = Speed of engine in rpm
- T = Torque in Nm

- In the case of Rope Brake System,
- Torque, $T = (W-S)R$
- Where, W = Dead weight or brake load in N
- S = Spring balance reading in N
- R = (Radius of the brake drum + diameter of the rope) in m
- In case of Prony Brake System,
- Torque, $T = W \times l$
- Where, W = Dead weight or brake load in N
- l = Effective distance of the load from the axis of rotation in meter.



Rope Brake System



Prony Brake System

BRAKE MEAN EFFECTIVE PRESSURE

- Which gives an indication of load on the engine.
- Brake mean effective pressure, bmep = $\frac{BP\ x\ 60}{LAnK}$
- BP = Brake power
- L = Stroke length in meter
- A = Area of the piston in m^2
- n = Number of power strokes per minute.
- K = Number of cylinders

FRICTIONAL POWER (FP)

- It is the difference between indicated power and brake power.
- FP = IP – BP
- IP = Indicated power
- BP = Brake power

BP is always less than IP, because,

- Pumping losses due to suction and exhaust.
- Mechanical losses in bearings.
- Power required to drive engine accessories such as fuel pump, oil pump etc.
- The above losses are known as frictional power.

Q.1. A two cylinder four stroke cycle IC engine is to be designed to develop 15 kW IP at 1200 rpm. The indicated mean effective pressure of the cycle is limited to 600 kPa. Determine the bore diameter and stroke of the engine. If stroke = 1.2 x bore diameter

- Given data:
- K = 2
- Stroke = 4
- IP = 15 kW = 15 x 10^3 W
- N = 1200 rpm
- P_m = 600 kPa = 600 x 10^3 N/m^2
- d = ?
- L = ?
- L = 1.2 d
- $IP = \frac{P_m L A n K}{60}$

- For 4-Stroke engine, n = N/2
- n = 1200/2
- n = 600 rpm
- $A = \frac{\pi}{4} d^2$
- $IP = \frac{P_m L A n K}{60}$
- $15 \times 10^3 = \frac{600 \times 10^3 \times 1.2\, d \times \frac{\pi}{4} d^2 \times 600 \times 2}{60}$
- d = 0.109 m = 109 mm
- Stroke length, L = 1.2 d = 1.2 x 109
- L = 130.8 mm

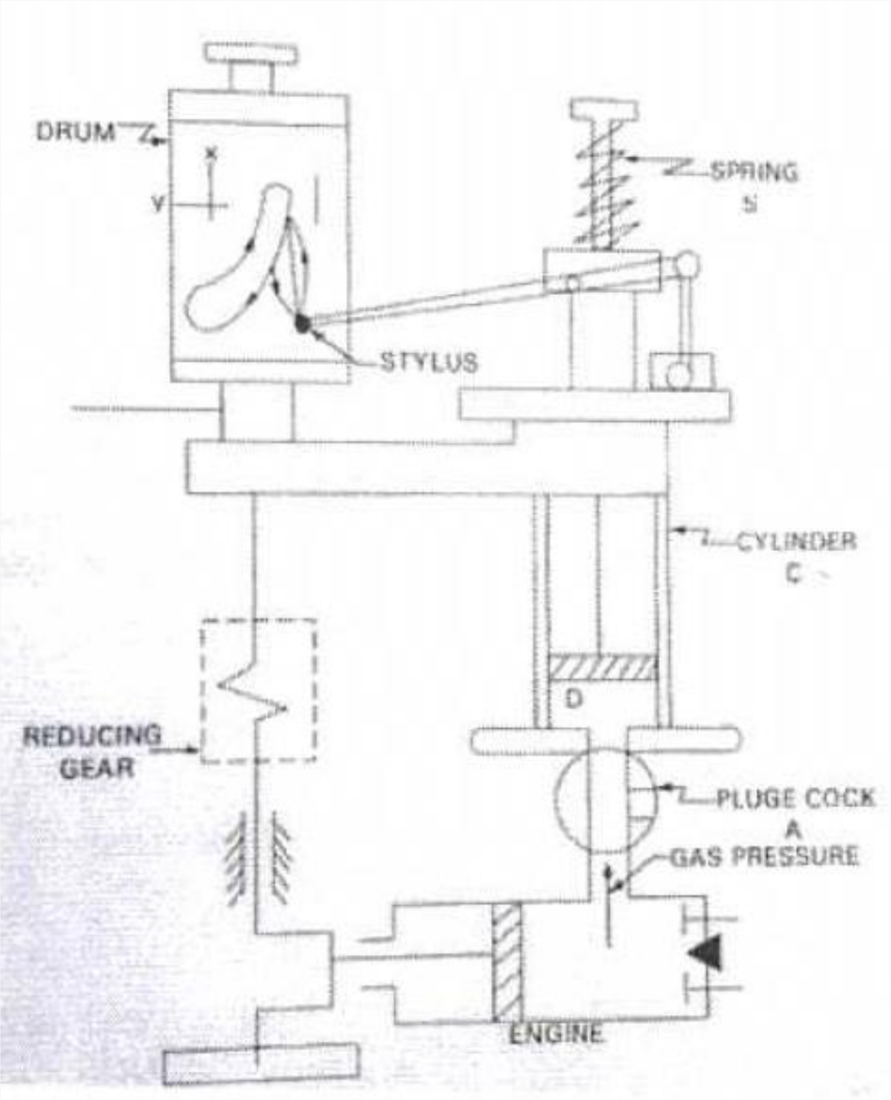
Q.2. An IC engine runs at 600 rpm. During a brake test the dead load on the brake drum is 0.3 kN and spring balance reads 0.03 kN. The brake drum diameter is 600 mm and rope diameter is 6 mm. Find the brake power developed?

- Given data:
- $N = 600$ rpm
- $W = 0.3$ kN $= 300$ N
- $S = 0.03$ kN $= 30$ N
- $D_{bd} = 600$ mm $= 0.6$ m
- $R_{bd} = 0.3$ m
- $d_r = 6$ mm $= 0.006$ m
- BP = ?
- $BP = \frac{2\pi NT}{60}$

- $T = (W-S)R$
- $R = R_{bd} + d_r$
- $R = 0.3 + 0.006 = 0.306$ m
- $T = (W-S)R = (300 - 30) \times 0.306$
- $T = 82.62$ Nm
- $BP = \frac{2\pi\ x\ 600\ x\ 82.62}{60}$
- $BP = 5191.16$ W
- $BP = 5.19$ kW

Explain how indicator diagram is obtained for IC engines.

- A cylinder C which is connected to an engine cylinder through a plug cock A.
- Piston D of this cylinder is attached to the top of the tension spring S with the help of a push rod.
- A magnifying mechanical linkage at the end of which a stylus is connected.
- The stylus traces diagram on the paper wrapped around the drum.
- The drum is directly driven by the engine crank shaft.
- The P-V diagram is obtained on this paper.



EFFICIENCIES OF IC ENGINES

MECHANICAL EFFICIENCY

- It is defined as the ratio of brake power (BP) to indicated power (IP) of an engine.
- $\eta_m = \frac{BP}{IP}$
- $IP = BP + FP$
- $BP = IP - FP$
- $\eta_m = \frac{IP - FP}{IP}$

- It is also defined as the ratio of brake thermal efficiency to indicated thermal efficiency.
- $\eta_m = \frac{\text{Brake thermal efficiency}}{\text{Indicated thermal efficiency}}$
- It is also defined as the ratio of brake mean effective pressure to indicated mean effective pressure.
- $\eta_m = \frac{\text{Brake mean effective pressure}}{\text{Indicated mean effective pressure}}$

INDICATED THERMAL EFFICIENCY

- It is the ratio of heat equivalent to indicated power per second to heat supplied by fuel per second.
- $\eta_i = \dfrac{\text{Heat equivalent to IP per sec}}{\text{FC X Cf}}$
- $\eta_i = \dfrac{IP}{FC \times C_f}$
- IP = Indicated power in kW
- FC = Fuel consumption or mass or volume of fuel burnt per sec. (kg/s or m^3/s)
- C_f = Calorific value of fuel in kJ/kg or kJ/m^3.

BRAKE THERMAL EFFICIENCY

- It is the ratio of heat equivalent to brake power per second to heat supplied by the fuel per second.
- $\eta_b = \dfrac{BP}{FC \times C_f}$
- BP = Brake power in kW
- FC = Fuel consumption or mass or volume of fuel burnt per sec. (kg/s or m^3/s)
- C_f = Calorific value of fuel in kJ/kg or kJ/m^3.

EFFICIENCY RATIO OR RELATIVE EFFICIENCY

- It is the ratio of indicated thermal efficiency to the air standard efficiency.
- $$\eta_R = \frac{\eta_i}{\eta_{air}}$$
- or
- It is the ratio of brake thermal efficiency to the air standard efficiency.
- $$\eta_R = \frac{\eta_b}{\eta_{air}}$$

FUEL CONSUMPTION

- The amount of fuel consumed in kg/hr
- $$\text{FC} = \frac{Xcc\ x\ \rho\ x\ 60\ x\ 60}{t\ x\ 1000}\ \text{kg/hr}$$
- *Xcc = Fuel consumed in cm^3*
- *ρ = Density of the fuel in g/cm^3*
- *t = Time in second.*

SPECIFIC FUEL CONSUMPTION (SFC)

- It is the fuel consumed given in kilograms of fuel per kWhr
- OR
- The fuel consumed/hr divided by the power gives the SFC.

Indicated specific fuel consumption (ISFC)

- It is the ratio of fuel consumption to the indicated power.
- ISFC = $\frac{FC}{IP}$ in kg/kWhr

Brake specific fuel consumption (BSFC)

- It is the ratio of fuel consumption to the brake power.
- BSFC = $\frac{FC}{BP}$ in kg/kWhr
- The value of BSFC is approximately 1.47 kg/kWhr for diesel engines and 1.85 kg/kWhr for petrol engines.

MORSE TEST

- This method is used to measure the indicated power without the use of an indicator, in multicylinder engines.
- The brake power of the engine is measured by cutting off each cylinder in turn.
- The cylinder of petrol engine is cut off by shorting the spark plug and in case of diesel engine this is done by cutting off the fuel supply to the required cylinder.
- The engine is first run under the required conditions of load, speed etc., and the brake power is measured accurately.
- Let this brake power be ‘BP’
- Now the first cylinder is cut out.
- So the engine speed will drop rapidly.
- The speed is brought to original speed by removing load on dynamometer.

- Under this condition (with one cylinder cut off), the brake power is measured. Let this be BP_1
- Now the first cylinder is put back in operation and the second cylinder is cut out.
- Load is adjusted to restore the original speed and brake power is determined. Let this be BP_2
- The same procedure is adopted for each cylinder in turn and in each case brake power is determined (BP_3, BP_4 etc.)
- Let us consider a four cylinder petrol engine coupled with hydraulic dynamometer to measure brake power.
- Let IP_1, IP_2, IP_3, IP_4 are indicated power of cylinders 1,2,3,and 4
- BP = Total brake power of all 4 cylinders.
- BP_1 = Total brake power of three cylinders with cylinder 1 cut off.
- BP_2 = Total brake power of three cylinders with cylinder 2 cut off.
- BP_3 = Total brake power of three cylinders with cylinder 3 cut off.
- BP_4 = Total brake power of three cylinders with cylinder 4 cut off.
- FP_1, FP_2, FP_3, FP_4 frictional power of each cylinders.

- If all cylinders are working,
- $BP = (IP_1 – FP_1) + (IP_2 – FP_2) + (IP_3 – FP_3) + (IP_4 – FP_4)$
- $= (IP_1 + IP_2 + IP_3 + IP_4) – (FP_1 + FP_2 + FP_3 + FP_4)$ ………..(1)
- Now if one cylinder is cut out, the IP of that cylinder is cut out.
- But, FP of this cylinder still exists. Therefore if the first cylinder is cut-out, brake power of the other three cylinders BP_1 is given by,
- $BP_1 = (IP_2 + IP_3 + IP_4) – (FP_1 + FP_2 + FP_3 + FP_4)$ ………..(2)
- Subtracting equation (2) from equation (1), we get
- $BP – BP_1 = IP_1$ (Indicated power of first cylinder)
- Similarly by cutting cylinders 2,3 and 4 in turn, IP_2, IP_3 and IP_4 can be calculated as below.
- $BP – BP_2 = IP_2$ (Indicated power of second cylinder)
- $BP – BP_3 = IP_3$ (Indicated power of third cylinder)
- $BP – BP_4 = IP_4$ (Indicated power of fourth cylinder)
- Since, total indicated power developed, $IP = IP_1 + IP_2 + IP_3 + IP_4$

Q.1. A four stroke four cylinder engine running at 2400 rpm gives 40 kW brake power. The average torque when one cylinder was cut out was 0.118 kNm. Determine the indicated thermal efficiency if the calorific value of fuel is 43000 kJ/kg and the engine uses 0.38 kg of petrol per brake power hours.

- Given Data:
- Stroke = 4
- K = 4
- N = 2400 rpm
- BP = 40 kW (For 4 cylinders)
- T = 0.118 kNm (Average torque for 3 cylinders)
- C_f = 43000 kJ/kg
- BSFC = 0.38 kg/kWhr

- BP for 3 cylinders when one cylinder cut out, $BP_1 = \frac{2\pi NT}{60}$
- $= \frac{2\pi \times 2400 \times 0.118}{60}$
- $BP_1 = 29.65$ kW
- $BP - BP_1 = IP_1$ (Indicated power of first cylinder)
- IP of one cylinder, $IP_1 = BP - BP_1$
- $= 40 - 29.65$
- $IP_1 = 10.35$ kW

- The total indicated power developed by the 4 cylinders,
- $IP = IP_1 \text{ x } 4$
- $= 10.35 \text{ x } 4$
- $IP = 41.4 \text{ kW}$
- $BSFC = \frac{FC}{BP}$
- $FC = BSFC \text{ x } BP$
- $= 0.38 \text{ x } 40$
- $FC = 15.2 \text{ kg/hr}$
- Indicated thermal efficiency,
- $\eta_i = \frac{IP}{FC \text{ x } C_f}$
- Here, FC in kg/s
- $FC = 15.2 \text{ kg/hr}$
- $= 15.2/(60 \text{ x } 60) \text{ kg/s}$
- $= 0.00422 \text{ kg/s}$
- $\eta_i = \frac{41.4}{0.00422 \text{ x } 43000}$
- $= 0.2281$
- $\eta_i = 22.81 \%$

Q.2. A single cylinder, 4 stroke cycle engine was tested and following results were obtained. Mean height of indicator diagram is 21 mm, indicator spring number is 27 kPa/mm, swept volume of cylinder is 14 litres, speed of engine is 396 rpm, brake load is 77 kg, and brake drum radius is 700 mm. Determine: (i) indicated power (ii) brake power (iii) mechanical efficiency.

- Given data:
- K = 1
- Stroke = 4
- h = 21 mm
- S = 27 kPa/mm
- Vs = 14 litres
- $= 14 \times 10^{-3} = 0.014\ m^3$
- $Vs = A \times L = 0.014\ m^3$
- N = 396 rpm
- n = N/2 = 396/2
- n = 198 rpm
- W = 77 kg
- Rbd = 700 mm = 0.7 m
- IP = ?
- BP = ?
- $\eta_m = ?$
- Indicated mean effective pressure,
- $P_m = h \times S$
- $= 21 \times 27$
- $P_m = 567$ kPa

(i) IP = $\frac{P_m L A n}{60}$

- $= \frac{567 \ x \ 0.014 \ x \ 198}{60}$
- IP = 26.2 kW

(ii) BP = $\frac{2\pi N T}{60}$

- T = (W-S)R
- Take, S = 0
- W = 77 kg
- = 77 x 9.81 N
- = 755.37 N
- T = (755.37-0)0.7
- T = 528.76 Nm

- BP = $\frac{2\pi \ x \ 396 \ x \ 528.76}{60}$
- BP = 21927.16 W
- BP = 21.92 kW
- (iii) $\eta_m = \frac{\text{BP}}{\text{IP}}$
- $= \frac{21.92}{26.2}$
- = 0.8366
- η_m = 83.66 %

Q.3. A petrol engine develops 7.5 kW IP. Fuel consumption is 2 kg/hr and calorific value of fuel is 42000 kJ/kg. If it's compression ratio is 6, calculate relative efficiency of the engine.

- Given data:
- Petrol engine , Since Otto cycle
- IP = 7.5 kW
- FC = 2 kg/hr
- FC = 2/(60 x 60) = 0.000555 kg/s
- C_f = 42000 kJ/kg
- r = 6
- $\eta_R = ?$
- Air standard efficiency of otto cycle,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}, \text{ (Take } \gamma = 1.4)$$

- $= 1 - \frac{1}{(6)^{1.4-1}}$

$= 1 - 0.4883$

- $= 0.5117$
- $\eta = 51.17\ \%$
- $\eta_R = \frac{\eta_i}{\eta_{air}}$
- $\eta_i = \frac{IP}{FC \times C_f}$
- $= \frac{7.5}{0.000555 \times 42000} = 0.3217$
- $\eta_i = 32.17\ \%$
- $\eta_R = \frac{0.3217}{0.5117} = 0.6286$
- $\eta_R = 62.86\ \%$

HEAT BALANCE SHEET

- Heat produced in the engine cylinder is not fully utilized to do external work.
- Some of the heat is carried away by the engine cooling system, lubricating system, exhaust gases and radiation.
- Friction losses are also there which consumes about 10% of the total heat produced.
- It should be noted that about 20% of the heat produced is utilized for turning the wheels.
- The complete record of heat supplied and rejected during a certain time by an IC engine is entered in a tabular form known as heat balance sheet.

- Heat balance can be prepared as explained below:-

1) Heat supplied by the fuel, Q_s

- $Q_s = FC \times C_f$
- FC = Mass of fuel consumed in kg/min or m^3/min
- C_f = Calorific value of fuel in kJ/kg

2) Heat equivalent of brake power (useful work), Q_{BP}

- $Q_{BP} = BP \times 60$ kJ/min

3) Heat carried away by the cooling water, Q_w

- $Q_w = m_w C_w (T_2 - T_1)$ in kJ/min
- m_w = Mass of cooling water circulated in kg/min
- C_w = Specific heat of cooling water
- C_w = 4.2 kJ/kgK
- T_1 = Inlet temperature of cooling water in K
- T_2 = Outlet temperature of cooling water in K

4) Heat carried away by the exhaust gases, Q_g

- $Q_g = m_g C_g (T_g - T_a)$ in kJ/min
- m_g = Mass of exhaust gases produced in kg/min
- C_g = Specific heat of exhaust gases in kJ/kgK
- T_g = Temperature of exhaust gases in Kelvin
- T_a = Room temperature (ambient temperature) in Kelvin

5) Unaccounted heat or heat to surroundings

- Unaccounted heat = $Q_s - (Q_{BP} + Q_w + Q_g)$

Heat balance (minute basis)

Heat supplied	kJ	%	Heat output	kJ	%
Heat supplied by the fuel, Q_s			1) Q_{BP}		
			2) Q_w		
			3) Q_g		
			4) Unaccounted heat		
Total		100	Total		100

Q.1. A single cylinder oil engine works on a 4 stroke cycle engine has a bore of 110 mm and the stroke of 130 mm and runs at 600 rpm. The mean effective pressure is 600 kPa. It consumes 10 cc of fuel in 28 s. The diesel oil used is having a C_f of 42000 kJ/kg and specific gravity is 0.85. The engine cooling water enters at a temperature of 18^0C and leaves at 60^0C. The quantity of cooling water circulated is 1.5 kg/min. The brake wheel diameter is 850 mm and rope diameter is 20 mm. The net load on the brake is 0.11 kN. The exhaust gas temperature is 420^0C and its specific heat is 1kJ/kgK. The air fuel ratio is 22:1 by weight. Room temperature is 30^0C. Calculate (i) IP (ii) BP (iii) Mechanical efficiency (iv) Indicated thermal efficiency (v) Draw a heat balance sheet on hour basis.

- Given data:
- K =1
- Stroke = 4
- d = 110 mm = 0.11 m
- L = 130 mm = 0.13 m
- N = 600 rpm
- P_m = 600 kPa = 600 x 10^3 N/m^2
- X = 10 cm^3
- t = 28 s
- C_f = 42000 kJ/kg
- S = 0.85
- $T_1 = 18^0C = 18 + 273 = 291$ K
- $T_2 = 60^0C = 60 + 273 = 333$ K
- m_w = 1.5 kg/min =1.5/60 = 0. 025 kg/s
- D_{bd} = 850 mm = 0.85 m, R_{bd} = 0.425 m
- d_{rope} = 20 mm = 0.02 m
- W = 0.11kN
- $T_g = 420^0C = 420 + 273 = 693$ K
- C_g = 1 kJ/kgK
- Air fuel ratio = 22:1
- $T_a = 30^0C = 30 + 273 = 303$ K

1) $IP = \frac{P_m L A n K}{60}$

- $A = \frac{\pi}{4} d^2 = \frac{\pi}{4} (0.11)^2 = 9.5 \times 10^{-3}\ m^2$
- $n = N/2$
- $n = 600/2 = 300$ rpm
- $IP = \frac{600 \times 103 x\ 0.13\ x\ 9.5 \times 10{-}3 x\ 300\ x\ 1}{60}$
- $= 3705$ W
- IP = 3.705 kW

2) $BP = \frac{2\pi N T}{60}$

- $T = W (R_{bd} + d_{rope})$
- $= 0.11 (0.425 + 0.02)$
- $= 0.0489$ kNm
- $BP = \frac{2\pi\ x\ 600\ x\ 0.0489}{60}$
- BP = 3.0724 kW

3) Mechanical efficiency, $\eta_m = \frac{BP}{IP}$

- $\eta_m = \frac{3.0724}{3.705} = 0.829$
- $\eta_m = 82.9\ \%$
- 4) Indicated thermal efficiency,

4) $\eta_i = \frac{IP}{FC \times C_f}$

- FC = Fuel consumption in kg/s
- $FC = \frac{Xcc\ x\ \rho\ x\ 60\ x\ 60}{t\ x\ 1000}$ kg/hr
- ρ = *Density of the fuel in g/cm*^{3}
- $S = \frac{\rho_{diesel}}{\rho_{water}}$

- $\rho_{water} = 1000\ kg/m^3$
- $= 1000\ \frac{1000}{10^6}\ g/cm^3$
- $\rho_{water} = 1\ g/cm^3$
- $S = \frac{\rho_{diesel}}{\rho_{water}}$
- $\rho_{diesel} = S \times \rho_{water}$
- $\rho_{diesel} = 0.85 \times 1$
- $\rho_{diesel} = 0.85\ g/cm^3$
- $FC = \frac{10 x 0.85 x 60 x 60}{28 x 1000}$ kg/hr
- FC = 1.09 kg/hr
- = 1.09 / (60 x 60) kg/s
- FC = 3.027×10^{-4} kg/s

- $\eta_i = \frac{IP}{FC \times C_f}$
- $= \frac{3.705}{3.027 \times 10{-}4 \times 42000} = 0.2914$
- $\eta_i = 29.14\ \%$

5) Heat balance in hour basis

a) Heat supplied by the fuel, Q_s

- $Q_s = FC \times C_f$
- $Q_s = 1.09 \times 42000$
- = 45780 kJ/hr

b) Heat equivalent of brake power (useful work), Q_{BP}

- Q_{BP} = BP = 3.0724 kW = 3.0724 kJ/s
- Q_{BP} = 3.0724 x 60 x 60 kJ/hr
- Q_{BP} = 11060.64 kJ/hr

- % of heat equivalent of BP,
- $\% \text{ BP} = \frac{Output}{Input} \text{ x } 100$
- $= \frac{Q_{BP}}{Q_s} \text{ x } 100$
- $= \frac{11060.64}{45780} \text{ x } 100$
- $\% \text{ BP} = 24.16\%$

c) Heat carried away by the cooling water, Q_w

- $Q_w = m_w C_w (T_2 - T_1)$
- $m_w = 0.025$ kg/s
- $= 0.025 \text{ x } 60 \text{ x } 60$ kg/hr
- $m_w = 90$ kg/hr
- $C_w = 4.2$ kJ/kgK
- $Q_w = 90 \text{ x } 4.2 (333 - 291)$
- $Q_w = 15876$ kJ/hr
- $\% \text{ } Q_w = \frac{Q_w}{Q_s} \text{ x } 100$
- $= \frac{15876}{45780} \text{ x } 100$
- $\% \text{ } Q_w = 34.68 \%$

d) Heat carried away by the exhaust gases, Q_g

- $Q_g = m_g C_g (T_g - T_a)$
- By using 1 kg of fuel, exhaust = 23 kg (since, air-fuel ratio is 22:1)
- So for 1.09 kg fuel, mass of the exhaust gas,
- $m_g = 1.09 \text{ x } 23$ kg/hr
- $m_g = 25.07$ kg/hr

- $Q_g = m_g C_g (T_g - T_a)$
- $= 25.07 \times 1 \times (693 - 303)$
- $Q_g = 9777.3$ kJ/hr
- $\% \, Q_g = \frac{Q_g}{Q_s} \times 100$
- $= \frac{9777.3}{45780} \times 100$
- $\% \, Q_g = 21.36 \, \%$

e) Unaccounted heat or heat to surroundings

- Unaccounted heat $= Q_s - (Q_{BP} + Q_w + Q_g)$
- $= 45780 - (11060.64 + 15876 + 9777.3)$
- Unaccounted heat = 9066.06 kJ/hr
- % Unaccounted heat = (9066.06/45780)x100
- % Unaccounted heat = 19.80 %

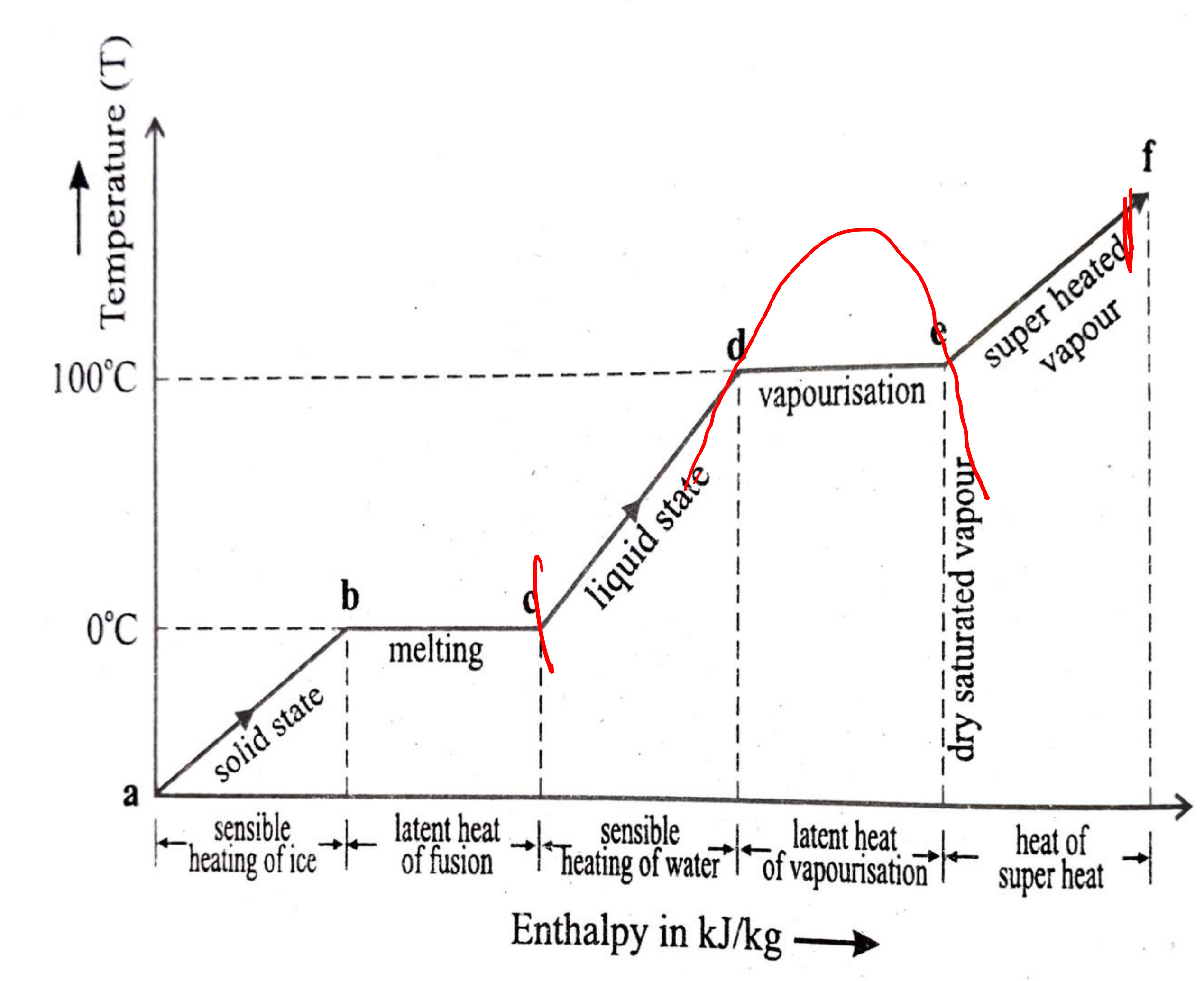
HEAT BALANCE SHEET IN HOUR BASIS

Heat Supplied	kJ	%	Heat Output	kJ	%
Q_s	45780	100	1) Q_{BP}	11060.64	24.16
			2) Q_w	15876	34.68
			3) Q_g	9777.3	21.36
			4) Unaccounted heat	9066.06	19.80
Total	45780	100	Total	45780	100

STEAM AND ITS PROPERTIES

FORMATION OF STEAM

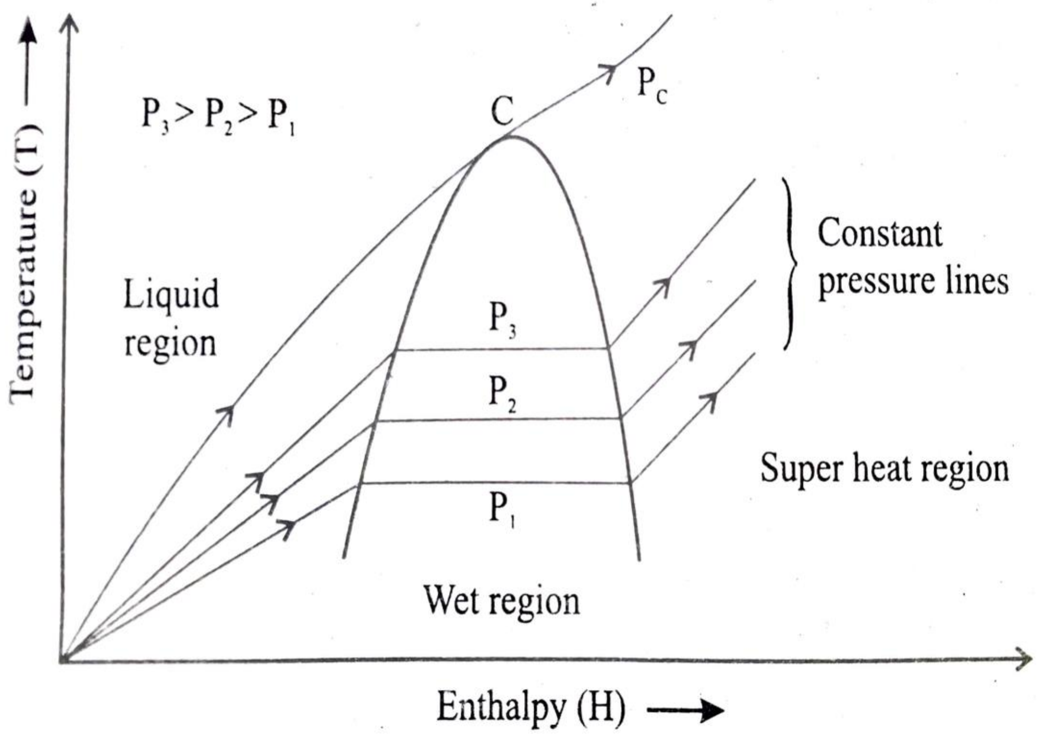
- Fig. shows the transformation of 1 kg of ice into super heated steam at constant pressure (atmospheric pressure), on the temperature enthalpy graph.
- Referring to figure, at point 'a' water is in the form of ice (solid state) at a temperature less than 0^0C .
- As heat is added, the temperature of ice increases till it reaches 0^0C and is shown by line a-b.



- Further addition of heat along the line b-c is used for melting the ice at constant temperature, and the amount of heat added is known as latent heat of fusion.
- Further addition of heat after the point 'c' increases the temperature of water and is continued till the temperature reaches to 100^0C ie; up to point 'd' - known as sensible heating.
- Further addition of heat after the point 'd' is used for vapourising the water and is continued till all the water is converted in to vapour (steam) at point 'e.
- Heat added during the process d-e is known as latent heat of vapourisation.
- The temperature at which the vapourisation of water takes place is known as boiling point temperature or saturation temperature.
- At point 'e' the steam is dry and saturated.
- Further addition of heat after the point 'e' increases the temperature of steam.
- The steam at a temperature above saturation temperature is known as "super heated steam"

PHASE TRANSFORMATION OF WATER ON HEATING: T-H DIAGRAM

- The boiling point of water (saturation temperature of steam) increases with increase in pressure while the latent heat of vapourisation decreases, as shown in Fig.
- The point 'C' on the (T-H) diagram is known as "critical point" where the latent heat of steam becomes zero and density of water is equal to density of steam.
- The pressure and temperature corresponding to the critical point "C" are known as critical pressure (Pc) and critical temperature (Tc) of steam. (Pc = 221.2 bar, Tc = 374.15°C)



Temperature - Enthalpy diagram representing transformation of water to super heated steam

USES OF STEAM

- For power generation as in case of steam engines or turbines.
- For heating as in case of heating installations for buildings.
- For industrial process work in chemical engineering, sugar and textile industry.
- For producing hot water required to be supplied in very cold areas.
- For the operation of power hammers, pile driving machines, hoisting rigs.
- For the operation of locomotives and ships.

TYPES OF STEAM

- SATURATED STEAM
- It is the steam at a temperature corresponding to the boiling point of water at the corresponding pressure.
- DRY SATURATED STEAM
- If saturated steam does not contains any water particles in it, then it is known as dry saturated steam.
- WET STEAM
- If saturated steam contains water particles in suspension, it is known as wet steam.
- SUPERHEATED STEAM
- The steam above the saturation temperature is known as super heated steam.

ENTHALPY OF STEAM

- It is the total heat absorbed by the steam from the freezing point of water to the saturation temperature plus the heat absorbed during evaporation.
- It is expressed in kJ/kg.
- Enthalpy of 1 kg of water or steam is called specific enthalpy.

SPECIFIC ENTHALPY OF UNSATURATED WATER

- It is the amount of heat required to raise the temperature of 1 kg of water from 0^0C to its actual temperature which is below its saturation temperature.
- $h_w = C_w (t_2 – t_1)$
- $C_w = 4.187$ kJ/kgK
- t_2 = Final temperature in ^{0}C
- t_1 = Initial temperature in ^{0}C
- = 0^0C
- $h_w = C_w \times t_2$

SPECIFIC ENTHALPY OF SATURATED WATER

- It is the quantity of heat required to raise the temperature of 1 kg of water at 0^0C to its boiling point or saturation temperature corresponding to the pressure applied.
- $h_f = C_w (t_s – t_1)$
- $C_w = 4.187$ kJ/kgK
- t_s = Saturation or boiling point temperature in ^{0}C
- t_1 = Initial temperature in ^{0}C
- = 0^0C
- $h_f = C_w \times t_s$

LATENT HEAT OF STEAM

- It is the quantity of heat in kJ required to convert 1 kg of water at its boiling point into dry saturated steam at the same pressure.
- It is represented by h_{fg}.

DRYNESS FRACTION

- It is the ratio of mass of dry steam to the total mass of wet steam.
- $x = \dfrac{\text{Mass of dry steam}}{\text{Total mass of steam}}$
- $x = \dfrac{m_g}{m_g + m_w}$
- m_g = Mass of dry steam
- m_w = Mass of water vapour in steam

Wetness fraction (1-x)

- It is the ratio of mass of water vapour in steam to the total mass of wet steam.
- $1 - x = \dfrac{m_w}{m_g + m_w}$

SPECIFIC ENTHALPY OF WET STEAM

- It is defined as the quantity of heat required to convert 1kg of water at 0^0C into the wet steam of given quantity at constant pressure.
- $h_{ws} = h_f + x\,(h_{fg})$

SPECIFIC ENTHALPY OF DRY SATURATED STEAM

- It is defined as the quantity of heat required to convert 1kg of water at 0^0C into dry saturated steam at given constant pressure.
- $h_g = h_f + h_{fg}$

SPECIFIC ENTHALPY OF SUPERHEATED STEAM

- It is defined as the quantity of heat required to convert 1kg of water at 0^0C into superheated steam at given temperature and pressure.
- $h_{sup} = h_g + C_s (t_{sup} - t_{sat})$
- $h_{sup} = h_f + h_{fg} + C_s (t_{sup} - t_{sat})$
- $(t_{sup} - t_{sat})$ is called degree of super heat.

SPECIFIC VOLUME

SPECIFIC VOLUME OF WET STEAM

- $V_{ws} = xV_g$
- V_g = Specific volume of dry steam

SPECIFIC VOLUME OF SUPERHEATED STEAM

- $V_{sup} = T_{sup} \text{ x } \frac{V_g}{T_{sat}}$
- $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- At constant pressure, $P_1 = P_2$
- $\frac{V_g}{T_{sat}} = \frac{V_{sup}}{T_{sup}}$

SPECIFIC ENTROPY

- **SPECIFIC ENTROPY OF UNSATURATED WATER (S_w)**
- $S_w = C_w \log_e \frac{T}{273}$
- **SPECIFIC ENTROPY OF SATURATED WATER (S_f)**
- $S_f = C_w \log_e \frac{T_{sat}}{273}$
- $S_{fg} = \frac{h_{fg}}{T_s}$
- **SPECIFIC ENTROPY OF WET STEAM (S_{ws})**
- $S_{ws} = S_f + x\, S_{fg}$
- **SPECIFIC ENTROPY OF DRY SATURATED STEAM (S_g)**
- $S_g = S_f + S_{fg}$
- **SPECIFIC ENTROPY OF SUPERHEATED STEAM (S_{sup})**
- $S_{sup} = S_g + C_{sup} \log_e \frac{T_{sup}}{T_{sat}}$

STEAM TABLES

- In engineering problem, for any fluid which is used as working fluid, the six basic thermodynamic properties required are, pressure (p), temperature (T), volume (v), internal energy (u), enthalpy (h) and entropy (s).
- These properties must be known at different pressure for analysing the thermodynamic cycles used for work producing devices.
- The values of these properties are determined theoretically or experimentally and are tabulated in the form of tables which are known as steam tables.
- Steam Tables.pdf

ENTHALPY-ENTROPY CHART OR MOLLIER DIAGRAM

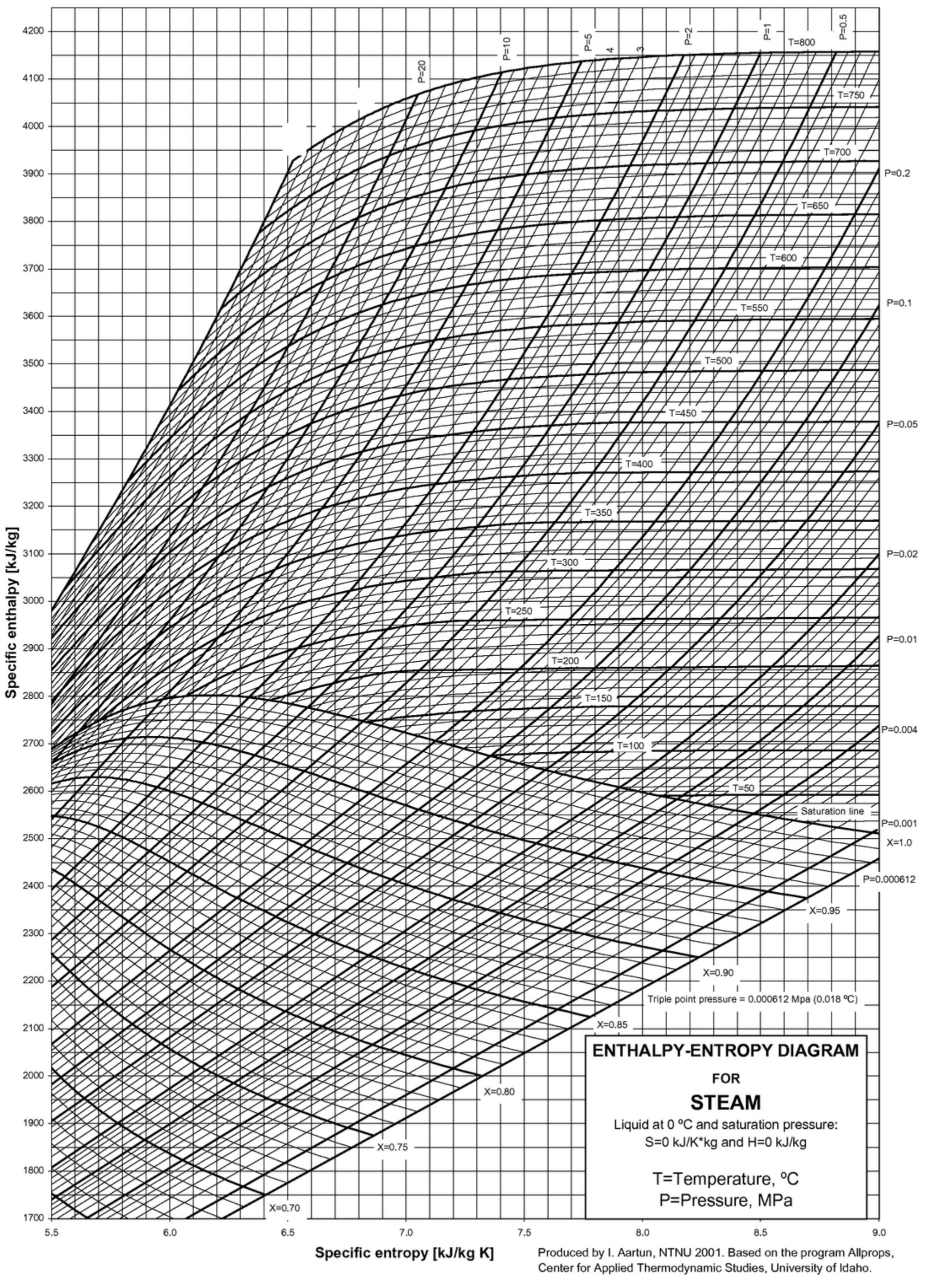
- It is a graphical representation of steam tables, in which specific entropy is plotted along the x-axis and specific enthalpy along the y-axis.
- The diagram is divided into two portions by a somewhat horizontal line termed as saturation curve.
- The lower portion (ie, wet steam region) contains the values of wet steam, whereas the upper portion (ie, superheated steam region) contains the values of super heated steam.
- A Mollier diagram has the following lines.

a) Dryness fraction lines.

b) Constant specific volume lines.

c) Constant pressure lines.

d) Constant temperature lines.


ENTHALPY-ENTROPY DIAGRAM
FOR
STEAM
Liquid at 0 ºC and saturation pressure:
S=0 kJ/K*kg and H=0 kJ/kg
T=Temperature, ºC
P=Pressure, MPa
Specific enthalpy [kJ/kg]
Specific entropy [kJ/kg K]
Saturation line
Triple point pressure = 0.000612 Mpa (0.018 ºC)
Produced by I. Aartun, NTNU 2001. Based on the program Allprops,
Center for Applied Thermodynamic Studies, University of Idaho.

Q.1 How much heat is needed to convert 1kg of feed water at 20^0C into dry saturated steam at 10 bar. Take specific heat of water as 4.187 kJ/kgK.

- Given data:
- m= 1 kg
- $t_2 = 20^0C$, $t_1 = 0^0C$
- P = 10 bar
- $C_w = 4.187$ kJ/kgK
- From steam table page no. 11, at 10 bar.
- $h_f = 762.6$ kJ/kg
- $h_{fg} = 2013.6$ kJ/kg
- $h_g = h_f + h_{fg}$
- $= 762.6 + 2013.6 = 2776.2$ kJ/kg

Saturated Water and Steam (Pressure) Tables

11

(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
5.2	153.3	0.001 095	0.361 06	646.5	2 102.7	2 749.2	1.875	4.931	6.806	**5.2**
5.4	154.8	0.001 096	0.348 44	652.8	2 098.1	2 750.9	1.890	4.903	6.793	**5.4**
5.6	156.2	0.001 098	0.336 69	658.8	2 093.7	2 752.5	1.904	4.877	6.781	**5.6**
5.8	157.5	0.001 099	0.325 72	664.7	2 089.3	2 754.0	1.918	4.851	6.769	**5.8**
6.0	158.8	0.001 101	0.315 46	670.4	2 085.1	2 755.5	1.931	4.827	6.758	**6.0**
6.2	160.1	0.001 102	0.305 84	676.1	2 080.8	2 756.9	1.944	4.803	6.747	**6.2**
6.4	161.4	0.001 104	0.296 80	681.5	2 076.7	2 758.2	1.956	4.780	6.736	**6.4**
6.6	162.6	0.001 105	0.288 29	686.8	2 072.7	2 759.5	1.968	4.757	6.725	**6.6**
6.8	163.8	0.001 107	0.280 26	692.0	2 068.8	2 760.8	1.980	4.735	6.715	**6.8**
7.0	165.0	0.001 108	0.272 68	697.1	2 064.9	2 762.0	1 992	4.713	6.705	**7.0**
7.2	166.1	0.001 110	0.265 50	702.0	2 061.2	2 763.2	2 003	4.693	6.696	**7.2**
7.4	167.2	0.001 111	0.258 70	706.9	2 057.4	2 764.3	2 014	4.672	6.686	**7.4**
7.6	168.3	0.001 112	0.252 24	711.7	2 053.7	2 765.4	2 025	4.652	6.677	**7.6**
7.8	169.4	0.001 114	0.246 10	716.3	2 050.1	2 766.4	2 035	4.633	6.668	**7.8**
8.0	170.4	0.001 115	0.240 26	720.9	2 046.5	2 767.4	2.046	4.614	6.660	**8.0**
8.2	171.4	0.001 116	0.234 69	725.4	2 043.0	2 768.4	2.056	4.595	6.651	**8.2**
8.4	172.4	0.001 118	0.229 38	729.9	2 039.6	2 769.4	2.066	4.577	6.643	**8.4**
8.6	173.4	0.001 119	0.224 31	734.2	2 036.2	2 770.4	2.075	4.560	6.635	**8.6**
8.8	174.4	0.001 120	0.219 46	738.5	2 032.8	2 771.3	2.085	4.542	6.627	**8.8**
9.0	175.4	0.001 121	0.214 82	742.6	2 029.5	2 772.1	2.094	4.525	6.619	**9.0**
9.2	176.3	0.001 123	0.210 37	746.8	2 026.2	2 773.0	2.103	4.509	6.612	**9.2**
9.4	177.2	0.001 124	0.206 10	750.8	2 023.0	2 773.8	2.112	4.492	6.604	**9.4**
9.6	178.1	0.001 125	0.202 01	754.8	2 019.8	2 774.6	2.121	4.476	6.597	**9.6**
9.8	179.0	0.001 126	0.198 08	758.7	2 016.7	2 775.4	2.130	4.460	6.590	**9.8**
10.0	179.9	0.001 127	0.194 30	762.6	2 013.6	2 776.2	2.138	4.445	6.583	**10.0**
10.5	182.0	0.001 130	0.185 48	772.0	2 006.0	2 778.0	2.159	4.407	6.566	**10.5**
11.0	184.1	0.001 133	0.177 39	781.1	1 998.6	2 779.7	2.179	4.371	6.550	**11.0**
11.5	186.0	0.001 136	0.170 02	789.9	1 991.4	2 781.3	2.198	4.336	6.534	**11.5**
12.0	188.0	0.001 139	0.163 21	798.4	1 984.3	2 782.7	2.216	4.303	6.519	**12.0**
12.5	189.8	0.001 141	0.156 96	806.7	1 977.5	2 784.2	2.234	4.271	6.505	**12.5**

- Enthalpy of 1 kg of feed water at 20^0C above 0^0C is,
- $h_w = C_w \, (t_2 – t_1)$
- $= 4.187 \, (20\text{-}0)$
- $= 83.74$ kJ/kg
- Since hat supplied to convert 1 kg of feed water at 20^0C into dry saturated steam at 10 bar is,
- $= h_g – h_w$
- $= 2776.2 – 83.74$
- $= 2692.46$ kJ/kg

Q.2. Determine the quantity of heat required to produce 1 kg of wet steam with dryness fraction 0.9 at a pressure of 6 bar from water at 25^0C.

- Given data:
- $m = 1$ kg
- $x = 0.9$
- $P = 6$ bar
- $t_2 = 25^0C$
- $t_1 = 0^0C$
- From steam table page no. 11, at 6 bar.
- $h_f = 670.4$ kJ/kg
- $h_{fg} = 2085.1$ kJ/kg

Saturated Water and Steam (Pressure) Tables

(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
5.2	153.3	0.001 095	0.361 06	646.5	2 102.7	2 749.2	1.875	4.931	6.806	**5.2**
5.4	154.8	0.001 096	0.348 44	652.8	2 098.1	2 750.9	1.890	4.903	6.793	**5.4**
5.6	156.2	0.001 098	0.336 69	658.8	2 093.7	2 752.5	1.904	4.877	6.781	**5.6**
5.8	157.5	0.001 099	0.325 72	664.7	2 089.3	2 754.0	1.918	4.851	6.769	**5.8**
6.0	158.8	0.001 101	0.315 46	670.4	2 085.1	2 755.5	1.931	4.827	6.758	**6.0**
6.2	160.1	0.001 102	0.305 84	676.1	2 080.8	2 756.9	1.944	4.803	6.747	**6.2**
6.4	161.4	0.001 104	0.296 80	681.5	2 076.7	2 758.2	1.956	4.780	6.736	**6.4**
6.6	162.6	0.001 105	0.288 29	686.8	2 072.7	2 759.5	1.968	4.757	6.725	**6.6**
6.8	163.8	0.001 107	0.280 26	692.0	2 068.8	2 760.8	1.980	4.735	6.715	**6.8**
7.0	165.0	0.001 108	0.272 68	697.1	2 064.9	2 762.0	1 992	4.713	6.705	**7.0**
7.2	166.1	0.001 110	0.265 50	702.0	2 061.2	2 763.2	2 003	4.693	6.696	**7.2**
7.4	167.2	0.001 111	0.258 70	706.9	2 057.4	2 764.3	2 014	4.672	6.686	**7.4**
7.6	168.3	0.001 112	0.252 24	711.7	2 053.7	2 765.4	2 025	4.652	6.677	**7.6**
7.8	169.4	0.001 114	0.246 10	716.3	2 050.1	2 766.4	2 035	4.633	6.668	**7.8**
8.0	170.4	0.001 115	0.240 26	720.9	2 046.5	2 767.4	2.046	4.614	6.660	**8.0**
8.2	171.4	0.001 116	0.234 69	725.4	2 043.0	2 768.4	2.056	4.595	6.651	**8.2**
8.4	172.4	0.001 118	0.229 38	729.9	2 039.6	2 769.4	2.066	4.577	6.643	**8.4**
8.6	173.4	0.001 119	0.224 31	734.2	2 036.2	2 770.4	2.075	4.560	6.635	**8.6**
8.8	174.4	0.001 120	0.219 46	738.5	2 032.8	2 771.3	2.085	4.542	6.627	**8.8**
9.0	175.4	0.001 121	0.214 82	742.6	2 029.5	2 772.1	2.094	4.525	6.619	**9.0**
9.2	176.3	0.001 123	0.210 37	746.8	2 026.2	2 773.0	2.103	4.509	6.612	**9.2**
9.4	177.2	0.001 124	0.206 10	750.8	2 023.0	2 773.8	2.112	4.492	6.604	**9.4**
9.6	178.1	0.001 125	0.202 01	754.8	2 019.8	2 774.6	2.121	4.476	6.597	**9.6**
9.8	179.0	0.001 126	0.198 08	758.7	2 016.7	2 775.4	2.130	4.460	6.590	**9.8**
10.0	179.9	0.001 127	0.194 30	762.6	2 013.6	2 776.2	2.138	4.445	6.583	**10.0**
10.5	182.0	0.001 130	0.185 48	772.0	2 006.0	2 778.0	2.159	4.407	6.566	**10.5**
11.0	184.1	0.001 133	0.177 39	781.1	1 998.6	2 779.7	2.179	4.371	6.550	**11.0**
11.5	186.0	0.001 136	0.170 02	789.9	1 991.4	2 781.3	2.198	4.336	6.534	**11.5**
12.0	188.0	0.001 139	0.163 21	798.4	1 984.3	2 782.7	2.216	4.303	6.519	**12.0**
12.5	189.8	0.001 141	0.156 96	806.7	1 977.5	2 784.2	2.234	4.271	6.505	**12.5**

- Enthalpy of 1 kg of wet steam at 6 bar and 0.9 dryness fraction above 0^0C.
- $h_{ws} = h_f + x\ h_{fg}$
- $= 670.4 + 0.9 \times 2085.1$
- $= 2544.29$ kJ/kg
- Enthalpy of 1 kg of feed water at 25^0C above 0^0C is,
- $h_w = C_w(t_2 - t_1)$
- $= 4.187\ (25 - 0)$
- $= 104.675$ kJ/kg
- Since heat supplied to convert 1 kg of water at 25^0C into wet steam at 0.9 dryness fraction at 6 bar is,
- $= h_{ws} - h_w$
- $= 2544.29 - 104.675$
- $= 2439.615$ kJ/kg

Q.3. Calculate the dryness fraction of steam which has 1.5 kg of water in suspension with 50 kg of steam.

- Given data:
- $m_w = 1.5$ kg
- $m_g = 50$ kg
- x = ?
- Dryness fraction,
- $x = \dfrac{m_g}{m_g + m_w}$
- $x = \dfrac{50}{50 + 1.5}$
- x = 0.9708

Q.4. Find the volume of 1 kg of steam at a pressure of 15 bar in each of the following cases, (i) when steam is dry saturated (ii) when steam is wet having dryness fraction of 0.9 (iii) when steam is superheated, the degree of superheat being 40^0C.

- Given data:
- m = 1 kg
- P = 15 bar
- V = ?
- (i) from steam table page no. 12, at 15 bar,
- $V_g = 0.13167\ m^3/kg$
- Ie, specific volume Vg of dry saturated steam at 15 bar is,
- $V_g = 0.13167\ m^3/kg$

(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
13.0	191.6	0.001 144	0.151 14	814.7	1 970.7	2 785.4	2.251	4.240	6.491	**13.0**
13.5	193.3	0.001 146	0.145 76	822.5	1 964.2	2 786.7	2.267	4.211	6.478	**13.5**
14.0	195.0	0.001 149	0.140 73	830.1	1 957.7	2 787.8	2.284	4.181	6.465	**14.0**
14.5	196.7	0.001 151	0.136 06	837.5	1 951.4	2 788.9	2.299	4.154	6.453	**14.5**
15.0	198.3	0.001 154	0.131 67	844.6	1 945.3	2 789.9	2.314	4.127	6.441	**15.0**
15.5	199.8	0.001 156	0.127 56	851.6	1 939.2	2 790.8	2.329	4.100	6.429	**15.5**
16.0	201.4	0.001 159	0.123 70	858.5	1 933.2	2 791.7	2.344	4.074	6.418	**16.0**
16.5	202.9	0.001 161	0.120 06	865.3	1 927.3	2 792.6	2.358	4.049	6.407	**16.5**
17.0	204.3	0.001 163	0.116 64	871.8	1 921.6	2 793.4	2.371	4.025	6.396	**17.0**
17.5	205.7	0.001 166	0.113 40	878.2	1 915.9	2 794.1	2.384	4.001	6.385	**17.5**
18.0	207.1	0.001 168	0.110 33	884.5	1 910.3	2 794.8	2.398	3.977	6.375	**18.0**
18.5	208.5	0.001 170	0.107 42	890.7	1 904.8	2 795.5	2.410	3.955	6.365	**18.5**
19.0	209.8	0.001 172	0.104 67	896.8	1 899.3	2 796.1	2.423	3.933	6.356	**19.0**
19.5	211.1	0.001 174	0.102 04	902.7	1 894.0	2 796.7	2.435	3.911	6.346	**19.5**
20.0	212.4	0.001 177	0.099 55	908.5	1 888.7	2 797.2	2.447	3.890	6.337	**20.0**
21.0	214.8	0.001 181	0.094 902	919.9	1 878.3	2 798.2	2.470	3.849	6.319	**21.0**
22.0	217.2	0.001 185	0.090 663	930.9	1 868.1	2 799.1	2.492	3.809	6.301	**22.0**
23.0	219.6	0.001 189	0.086 780	941.6	1 858.2	2 799.8	2.514	3.771	6.285	**23.0**
24.0	221.8	0.001 193	0.083 209	951.9	1 848.5	2 800.4	2.534	3.735	6.269	**24.0**
25.0	223.9	0.001 197	0.079 915	961.9	1 839.1	2 801.0	2.554	3.699	6.253	**25.0**
26.0	226.0	0.001 201	0.076 865	971.7	1 829.7	2 801.4	2.574	3.665	6.239	**26.0**
27.0	228.1	0.001 205	0.074 033	981.2	1 820.5	2 801.7	2.592	3.632	6.224	**27.0**
28.0	230.0	0.001 209	0.071 396	990.5	1 811.5	2 802.0	2.611	3.600	6.211	**28.0**
29.0	232.0	0.001 213	0.068 935	999.5	1 802.7	2 802.2	2.628	3.569	6.197	**29.0**
30.0	233.8	0.001 216	0.066 632	1 008.3	1 794.0	2 802.3	2.646	3.538	6.184	**30.0**
31.0	235.7	0.001 220	0.064 473	1 017.1	1 785.4	2 802.3	2.662	3.509	6.171	**31.0**
32.0	237.4	0.001 224	0.062 443	1 025.4	1 776.9	2 802.3	2.679	3.480	6.159	**32.0**
33.0	239.2	0.001 227	0.060 533	1 033.7	1 768.6	2 802.3	2.694	3.452	6.146	**33.0**

- (ii) when steam is wet having dryness fraction 0.9, specific volume of wet steam is,
- $V_{ws} = x\ V_g$
- $= 0.9 \times 0.13167$
- $= 0.118503\ m^3/kg$
- (iii) Degree of superheat,
- $T_{sup} - T_{sat} = 40^0C$
- $V_{sup} = T_{sup} \times \frac{V_g}{T_{sat}}$
- From steam table page no. 12 corresponding to pressure at 15 bar,
- $T_{sat} = 198.3^0C$
- $= 198.3 + 273 = 471.3\ K$
- $T_{sup} = 40 + 471.3 = 511.3\ K$
- $V_{sup} = 511.3 \times \frac{0.13167}{471.3}$
- $= 0.1426\ m^3/kg$

Q.5. Calculate the total heat of 5 kg of steam at an absolute pressure of 8 bar having dryness fraction of 0.8. Also calculate heat required to convert the steam in to dry and saturated steam.

- Given data:
- $m = 5$ kg
- $P = 8$ bar
- $x = 0.8$
- $h_{ws} = ?$
- $h_g = ?$
- From steam table page no. 11, corresponding to 8 bar,
- $h_f = 720.9$ kJ/kg
- $h_{fg} = 2046.5$ kJ/kg
- $h_g = 2767.4$ kJ/kg

Saturated Water and Steam (Pressure) Tables

(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
5.2	153.3	0.001 095	0.361 06	646.5	2 102.7	2 749.2	1.875	4.931	6.806	**5.2**
5.4	154.8	0.001 096	0.348 44	652.8	2 098.1	2 750.9	1.890	4.903	6.793	**5.4**
5.6	156.2	0.001 098	0.336 69	658.8	2 093.7	2 752.5	1.904	4.877	6.781	**5.6**
5.8	157.5	0.001 099	0.325 72	664.7	2 089.3	2 754.0	1.918	4.851	6.769	**5.8**
6.0	158.8	0.001 101	0.315 46	670.4	2 085.1	2 755.5	1.931	4.827	6.758	**6.0**
6.2	160.1	0.001 102	0.305 84	676.1	2 080.8	2 756.9	1.944	4.803	6.747	**6.2**
6.4	161.4	0.001 104	0.296 80	681.5	2 076.7	2 758.2	1.956	4.780	6.736	**6.4**
6.6	162.6	0.001 105	0.288 29	686.8	2 072.7	2 759.5	1.968	4.757	6.725	**6.6**
6.8	163.8	0.001 107	0.280 26	692.0	2 068.8	2 760.8	1.980	4.735	6.715	**6.8**
7.0	165.0	0.001 108	0.272 68	697.1	2 064.9	2 762.0	1 992	4.713	6.705	**7.0**
7.2	166.1	0.001 110	0.265 50	702.0	2 061.2	2 763.2	2 003	4.693	6.696	**7.2**
7.4	167.2	0.001 111	0.258 70	706.9	2 057.4	2 764.3	2 014	4.672	6.686	**7.4**
7.6	168.3	0.001 112	0.252 24	711.7	2 053.7	2 765.4	2 025	4.652	6.677	**7.6**
7.8	169.4	0.001 114	0.246 10	716.3	2 050.1	2 766.4	2 035	4.633	6.668	**7.8**
8.0	170.4	0.001 115	0.240 26	720.9	2 046.5	2 767.4	2.046	4.614	6.660	**8.0**
8.2	171.4	0.001 116	0.234 69	725.4	2 043.0	2 768.4	2.056	4.595	6.651	**8.2**
8.4	172.4	0.001 118	0.229 38	729.9	2 039.6	2 769.4	2.066	4.577	6.643	**8.4**
8.6	173.4	0.001 119	0.224 31	734.2	2 036.2	2 770.4	2.075	4.560	6.635	**8.6**
8.8	174.4	0.001 120	0.219 46	738.5	2 032.8	2 771.3	2.085	4.542	6.627	**8.8**
9.0	175.4	0.001 121	0.214 82	742.6	2 029.5	2 772.1	2.094	4.525	6.619	**9.0**
9.2	176.3	0.001 123	0.210 37	746.8	2 026.2	2 773.0	2.103	4.509	6.612	**9.2**
9.4	177.2	0.001 124	0.206 10	750.8	2 023.0	2 773.8	2.112	4.492	6.604	**9.4**
9.6	178.1	0.001 125	0.202 01	754.8	2 019.8	2 774.6	2.121	4.476	6.597	**9.6**
9.8	179.0	0.001 126	0.198 08	758.7	2 016.7	2 775.4	2.130	4.460	6.590	**9.8**
10.0	179.9	0.001 127	0.194 30	762.6	2 013.6	2 776.2	2.138	4.445	6.583	**10.0**
10.5	182.0	0.001 130	0.185 48	772.0	2 006.0	2 778.0	2.159	4.407	6.566	**10.5**
11.0	184.1	0.001 133	0.177 39	781.1	1 998.6	2 779.7	2.179	4.371	6.550	**11.0**
11.5	186.0	0.001 136	0.170 02	789.9	1 991.4	2 781.3	2.198	4.336	6.534	**11.5**
12.0	188.0	0.001 139	0.163 21	798.4	1 984.3	2 782.7	2.216	4.303	6.519	**12.0**
12.5	189.8	0.001 141	0.156 96	806.7	1 977.5	2 784.2	2.234	4.271	6.505	**12.5**

- Specific enthalpy of wet steam,
- $h_{ws} = h_f + x\, h_{fg}$
- $h_{ws} = 720.9 + 0.8 \times 2046.5$
- $= 2358.1$ kJ/kg
- Total heat of 5 kg of steam = 5 x 2358.1
- = 11790.5 kJ
- Total heat of 5 kg of dry saturated steam
- = 5 x hg
- = 5 x 2767.4
- = 13837 kJ

ASSIGNMENT 2 (SUBMIT ON 21/05/21)

- 1. Explain the working of single cylinder double acting steam engine with neat sketch.
- 2. Explain the working of thermodynamic vapour cycle with P-V, T-S and schematic diagrams.

a) Carnot cycle

b) Rankine cycle

STEAM ENGINES

- It is a heat engine which converts heat energy into mechanical energy.
- The heat being carried into the engine through the medium of steam.
- Steam is used as the working substance.
- In reciprocating steam engine the heat energy in the steam is converted into mechanical work by the reciprocating motion of the piston in the cylinder.
- As combustion of fuel take place outside the engine cylinder it is also called as an external combustion engine.

CLASSIFICATION OF STEAM ENGINE

1) According to number of working strokes

- Single acting steam engines
- Double acting steam engines

2) According to the position of the cylinder

- Horizontal steam engine
- Vertical steam engine

3) According to speed of the engine

- Low speed
- Medium speed
- High speed

4) According to the type of exhaust

- Condensing steam engines
- Non-condensing steam engines

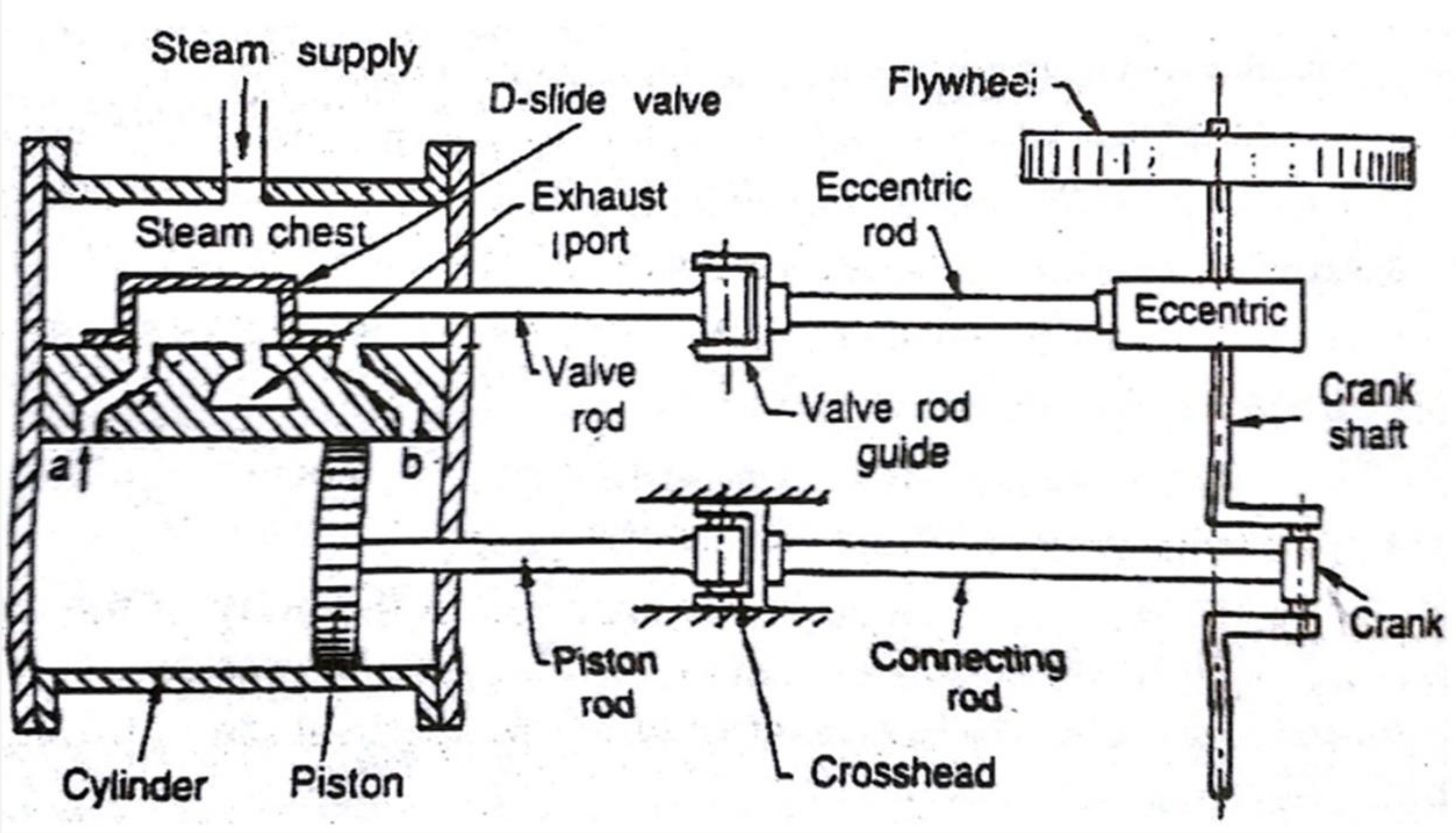
5) According to the expansion of steam inside the engine cylinder

- Simple steam engines
- Compound steam engines

IMPORTANT PARTS

- Frame:- It is a heavy cast iron part, which held all the stationary and moving parts of the engine in correct position.
- Cylinder:- It is made by cast iron, in which the piston reciprocates.
- Steam chest:- It is an integral part of the cylinder. It supplies steam to the cylinder by using D-slide valve.
- D-slide valve:- It moves in the steam chest. Its function is to connect the inlet and outlet port to the cylinder.
- Piston:- It is a cylindrical disc which reciprocates inside the cylinder. It converts the heat energy of the steam into mechanical work.
- Steam Engine works.mp4

SINGLE CYLINDER DOUBLE ACTING STEAM ENGINE



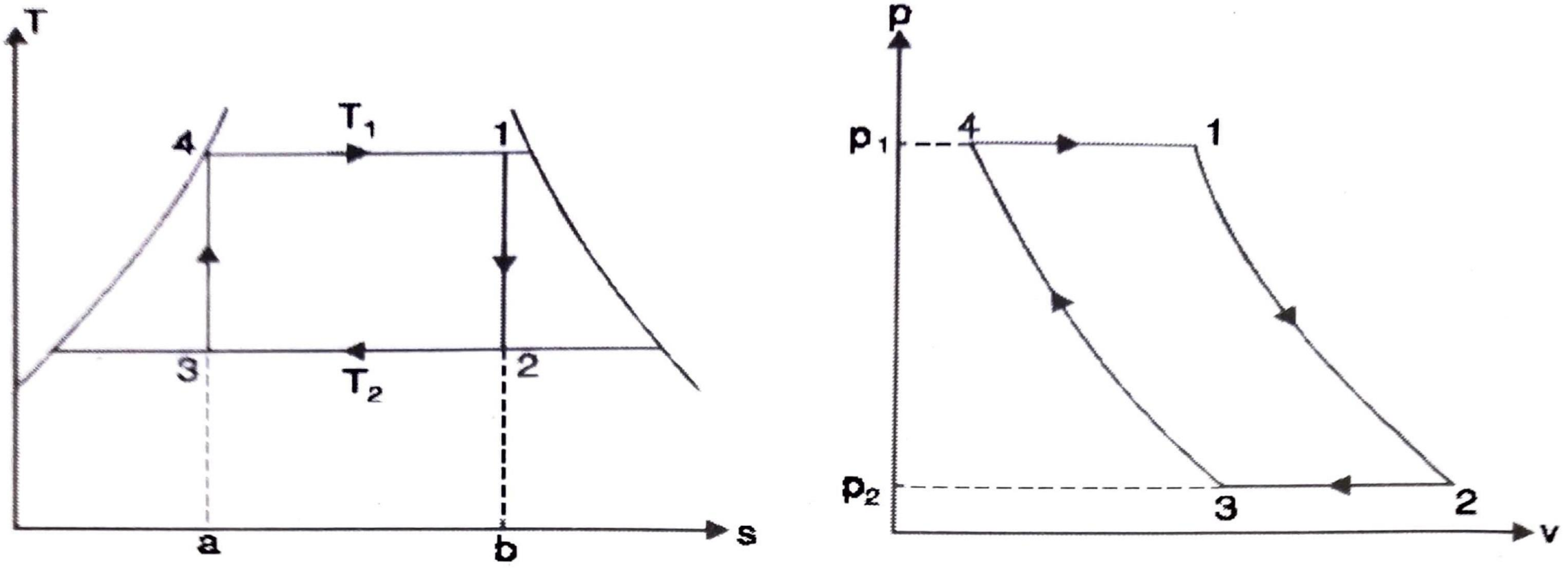
WORKING

- Working Model of Stephenson's STEAM ENGINE made of GLASS ! Rare!.mp4
- The super heated steam at high pressure from the steam boiler is fed to the steam chest.
- This steam is supplied to the engine cylinder through the inlet port on the left side of the piston.
- Now the piston moves from left to right side.
- At this time the slide valve covers the exhaust port and the second inlet port(b).
- When the piston reaches near the end of the cylinder the first inlet port (a) closes and opens the second inlet port (b).
- Now the steam enters the right side of the piston.
- This forces the piston from right to left and at the same time the exhaust steam goes out through the exhaust pipe.

THERMODYNAMIC VAPOUR CYCLES

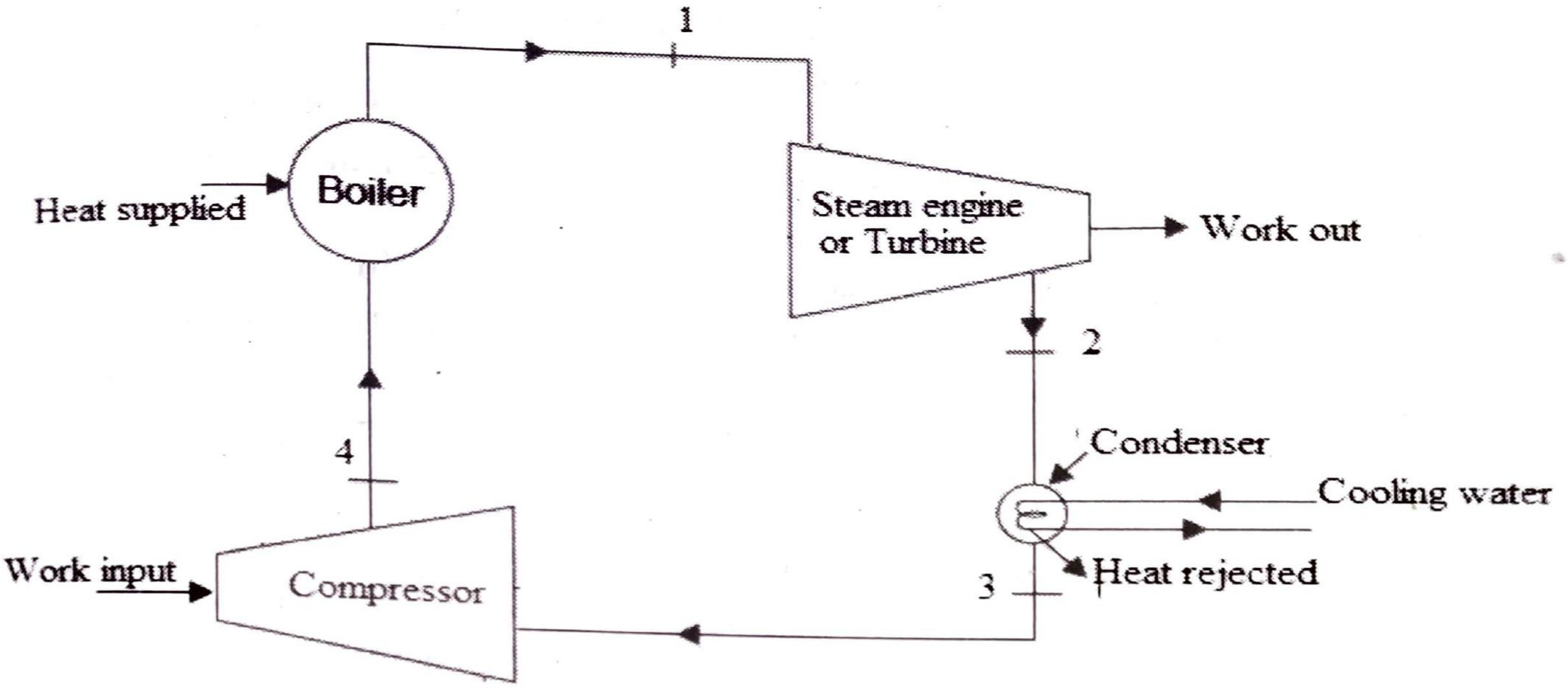
- Carnot Cycle
- Rankine cycle

CARNOT CYCLE WITH STEAM AS WORKING SUBSTANCE



Carnot cycle on *T-s* and *p-V* diagrams.

- The Carnot cycle is the most efficient cycle operating between two specified temperature levels – it adopted as an ideal cycle.
- Steam is the working fluid in the Carnot vapour cycle.
- Consider 1 kg of saturated water at pressure p_4, and absolute temperature T_4, as represented by point 4 in the figure.
- The cycle is completed by the following four processes:
- 4-1 Process (Isothermal Expansion)
- 1-2 Process (Adiabatic Expansion)
- 2-3 Process (Isothermal Compression)
- 3-4 Process (Adiabatic Compression)



Schematic diagram of Carnot engine

PROCESS 4-1 (ISOTHERMAL EXPANSION)

- The water is isothermally converted into dry saturated steam, at a constant temperature (T_4) and pressure (p_4).
- Dry state of steam is expressed in point 1.
- It means that the temperature T_1 (i.e., at point 1) and pressure p_1 (i.e., at point 1) is equal to temperature T_4 and pressure p_4 respectively.
- This isothermal expansion is represented by curve 4-1 on p-v and T-s diagram in the figure.
- We know that the heat is absorbed by water during its conversion into dry steam is its latent heat.

PROCESS 1-2 (ADIABATIC EXPANSION)

- The dry steam now expands adiabatically.
- The pressure and temperature drop from p_1 to p_2 and T_1 to T_2.
- As no heat is supplied or rejected during this process, there is no change of entropy.
- The adiabatic expansion is represented by the curve 1-2 as shown in the figure.

PROCESS 2-3 (ISOTHERMAL COMPRESSION)

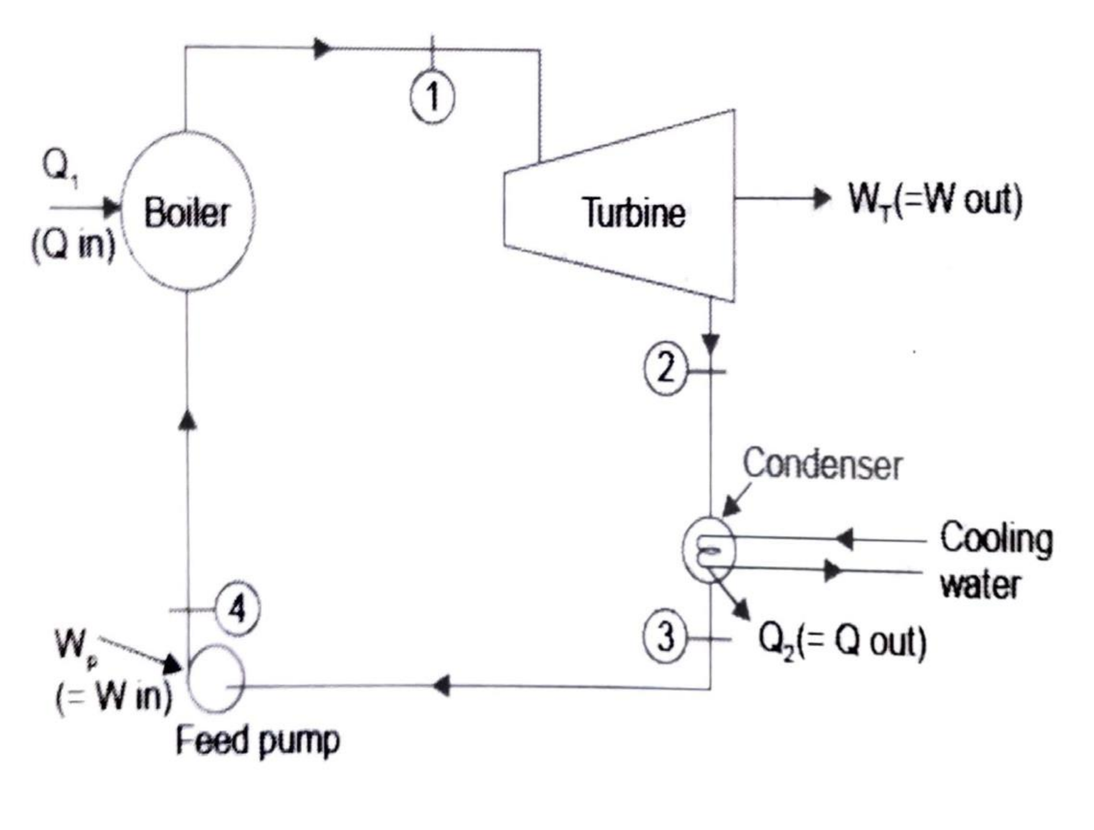
- The wet steam is now isothermally compressed at constant temperature (T_2) and pressure (p_2).
- It means that the temperature T_3 (i.e., at point 3) and pressure p_3 (i.e., at point 3) is equal to the temperature T_2 and pressure p_2 respectively.
- This isothermal compression is represented by the curve 2-3 on p-v and T-s diagrams as shown in the figure.

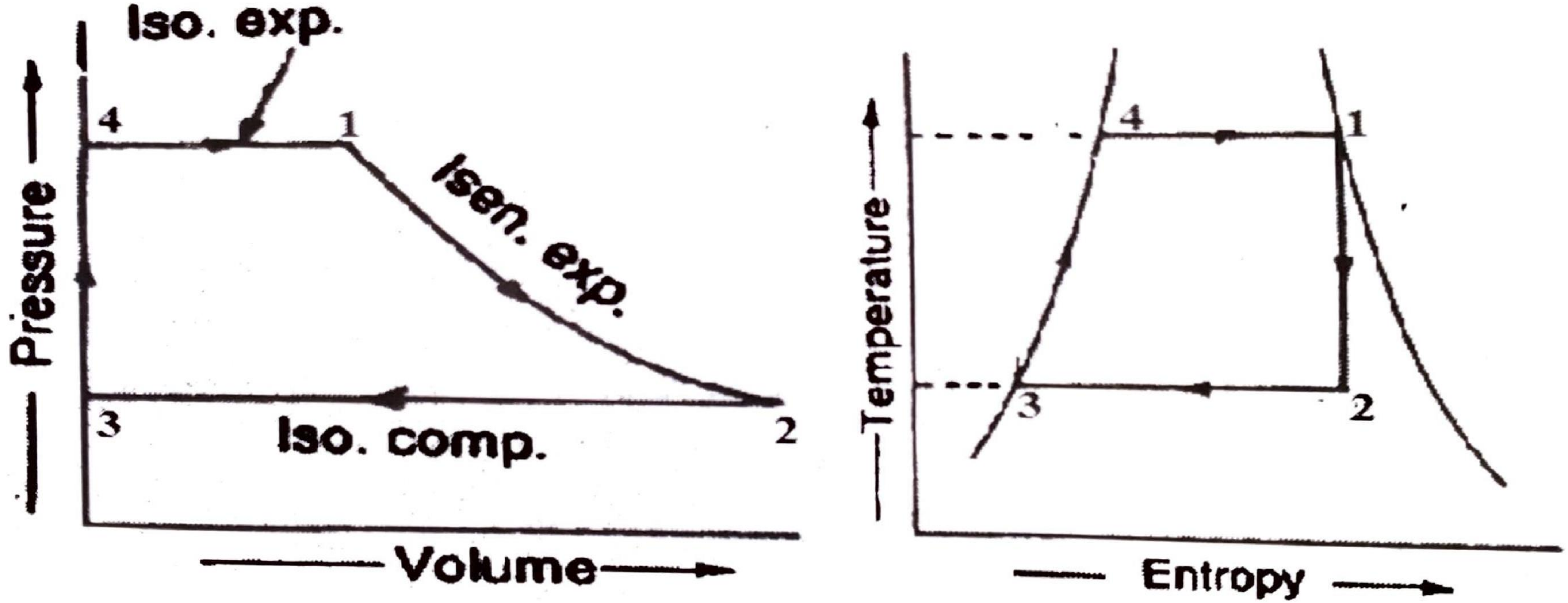
PROCESS 3-4 (ADIABATIC COMPRESSION)

- The wet steam at point 3 is finally compressed adiabatically, till it returns back to its original state (point 4).
- The pressure and temperature rise from p_3 to p_4 and T_3 to T_4 respectively.
- The adiabatic compression is represented by the curve 3-4 as shown in the figure.
- Since no heat is absorbed or rejected, therefore entropy remains constant. This completes the cycle.

RANKINE CYCLE

- Rankine cycle is the theoretical cycle on which the steam turbine (or engine) works.
- It is an ideal cycle used for comparing the performance of steam power plants.
- It is a modified form of Carnot cycle, in which the condensation process 2-3 is Continued until the steam is condensed to water.
- The schematic diagram, p-v diagram and T-s diagram is shown in the figure.





p-v and T-s diagram

WORKING

- Consider l kg of saturated water at pressure p_4 and temperature T_4 as represented by point 4 in the Fig. The cycle is completed by the following four processes.

Process 4-1:- Constant pressure heat addition in a boiler

- The saturated water is isothermally converted to dry saturated steam in a boiler, and the heat is absorbed at a constant temperature T_1 and pressure p_1.
- The dry state of steam is represented by the point 1. (i.e: $T_4 = T_1$ and $p_1 = P_4$)

Process 1-2:- Isentropic expansion in a turbine

- The dry saturated steam at point 1, now expands isentropically in an engine or turbine.
- The pressure and temperature falls from p_1 to p_2 and T_1 to T_2 respectively with a dryness fraction x_2.
- Since no heat is supplied or rejected during this process, therefore there is no change of entropy.
- The isentropic expansion is represented by 1-2.

Process 2-3:- Constant pressure heat rejection in a condenser

- The wet steam at point 2 is now isothermally condensed in a condenser and the heat is rejected at constant temperature T_2 and pressure p_2 until the whole steam is condensed into water.
- It means that the temperature T_3 and pressure P_3 is equal to T_2 and p_2 respectively.
- The isothermal process is represented by 2-3 on p-v and T-s diagram as shown.
- The heat rejected by steam is its latent heat.

Process 3-4:- Constant volume heat addition in pump

- The water at point 3 is now compressed by a pump at constant volume from temperature T_3 to T_4.
- Its pressure also rises from p_3 to p_4.
- This warming operation is represented by the curve 3-4 on p-v and T-s diagram.
- The heat absorbed by water during this operation is equal to the sensible heat or liquid heat corresponding to pressure P_4

STEAM NOZZLE

- Steam nozzle is an insulated passage of varying cross-sectional area through which heat energy (Enthalpy), pressure of steam is converted into kinetic energy.
- Functions of Nozzle :-

✓The main function of the steam nozzle is to convert heat energy to kinetic energy.

✓To direct the steam at high velocity into blades of turbine at required angle.

- Applications :-

✓Steam & gas turbines are used to produces a high velocity jet.

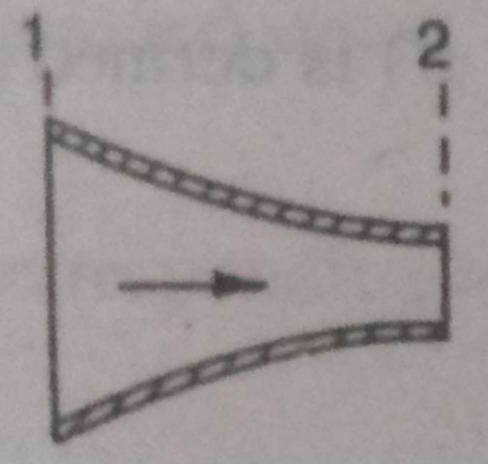
✓Jet engines and rockets to produce thrust (propulsive force).

TYPES OF STEAM NOZZLES

1) Convergent nozzle
2) Divergent nozzle
3) Convergent - divergent nozzle

CONVERGENT NOZZLE

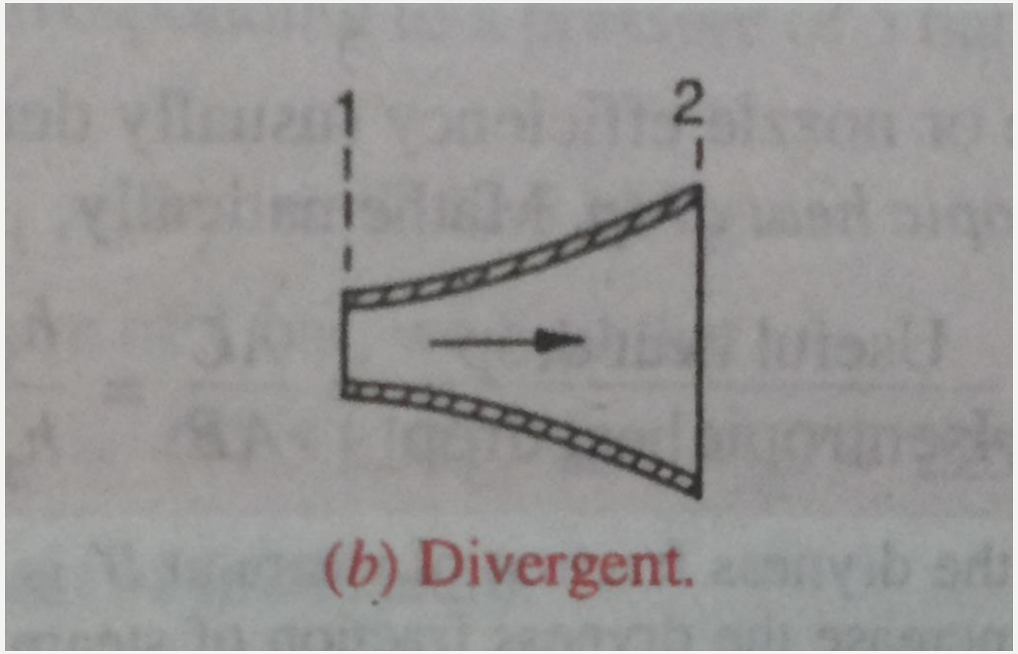
- When the cross section of a nozzle decreases continuously from entrance to exit is called convergent nozzle.



(a) Convergent.

DIVERGENT NOZZLE

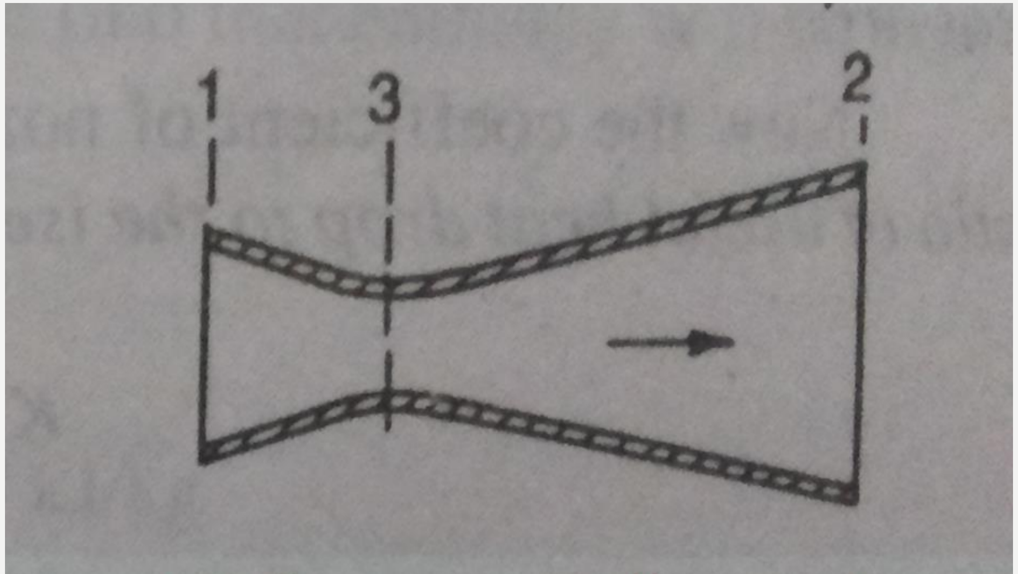
- When the cross section of a nozzle increases continuously from entrance to exit is called divergent nozzle.



(*b*) Divergent.

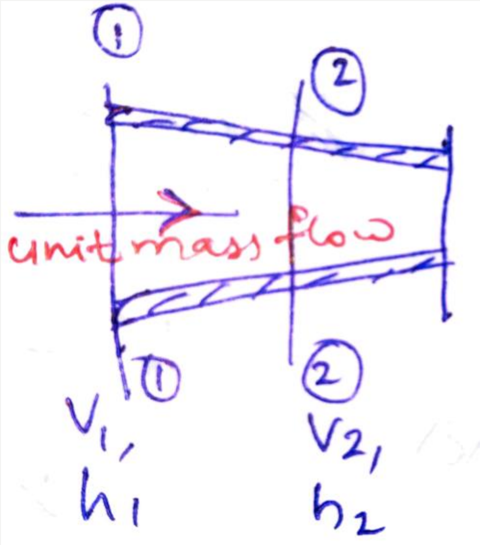
CONVERGENT - DIVERGENT NOZZLE

- When the cross section of a nozzle first decreases from entrance to throat, and then increases from throat to exit is called convergent - divergent nozzle.
- This type of nozzle is widely used in various types of steam turbines.



(c) Convergent-divergent.

VELOCITY OF STEAM FLOWING THROUGH A NOZZLE



- Consider a unit mass flow of steam through a nozzle.
- Let, V_1 = Velocity of steam at the entrance of nozzle in m/s.
- V_2 = Velocity of steam at any section in m/s.
- h_1 = Enthalpy or total heat entering the nozzle in kJ/kg
- h_2 = Enthalpy or total heat at the section considered in kJ/kg
- By steady flow energy equation in a nozzle, Energy at inlet = Energy at outlet
- KE + PE + u + Flow work + $\dot{Q}$ = KE + PE + u + Flow work + $\dot{W}$ + Losses
- $\dot{Q}$ = Heat transfer per unit mass
- $\dot{W}$ = Workdone per unit mass
- u = Internal energy, Flow work = pv

- Enthalpy, $h = u + pv$
- $h_1 + KE + PE + \dot{Q} = h_2 + KE + PE + \dot{W} + \text{Losses}$
- In nozzle expansion takes place isentropically, ie, $Q = 0$
- No work is done in the nozzle, ie, $W = 0$
- $h_1 + KE + PE = h_2 + KE + PE + \text{Losses}$
- PE = same (same height), cancels each other
- $h_1 + KE = h_2 + KE + \text{Losses}$
- $KE = \frac{1}{2} mV^2$
- $\quad = \frac{1}{2} \text{ x } 1 \text{ x } V^2$
- $\quad = \frac{V^2}{2} \text{ J}$
- $KE = \frac{1}{1000} \left(\frac{V^2}{2}\right) \text{ kJ}$

- $h_1 + \frac{1}{1000}\left(\frac{V_1^2}{2}\right) = h_2 + \frac{1}{1000}\left(\frac{V_2^2}{2}\right)$ + Losses
- Neglecting losses in a nozzle,
- $h_1 + \frac{1}{1000}\left(\frac{V_1^2}{2}\right) = h_2 + \frac{1}{1000}\left(\frac{V_2^2}{2}\right)$
- $\frac{1}{1000}\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) = h_1 - h_2$
- $\frac{1}{2000}(V_2^2 - V_1^2) = h_1 - h_2$
- $V_2^2 - V_1^2 = 2000\ (h_1 - h_2)$
- $V_2^2 = V_1^2 + 2000\ (h_1 - h_2)$
- $V_2 = \sqrt{V_1^2 + 2000\ (h_1 - h_2)}$
- $V_2 = \sqrt{V_1^2 + 2000\ h_d}$

- Where,
- h_d = Enthalpy or heat drop during expansion of steam in a nozzle.
- $h_d = (h_1 - h_2)$
- Since entrance velocity or velocity of approach (V_1) is negligible as compared to V_2.
- Since, $V_2 = \sqrt{2000\ h_d}$
- $V_2 = 44.72\sqrt{h_d}$
- If friction loss is considered,
- $V_2 = 44.72\sqrt{K\ h_d}$
- Where, K = nozzle efficiency