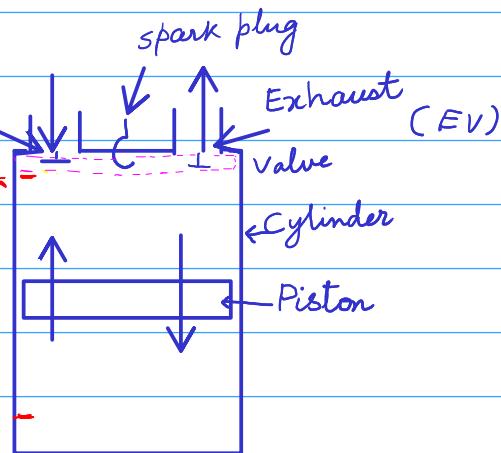


Thermodynamics ME22002 3-1-0-4

Process 1 EV closed, IV open.

Piston ↓

Inside the chamber air+fuel (IV) value or air is getting filled up.
 $A \rightarrow B$



Process 2 EV closed, IV closed

Piston ↑ $B \rightarrow A$

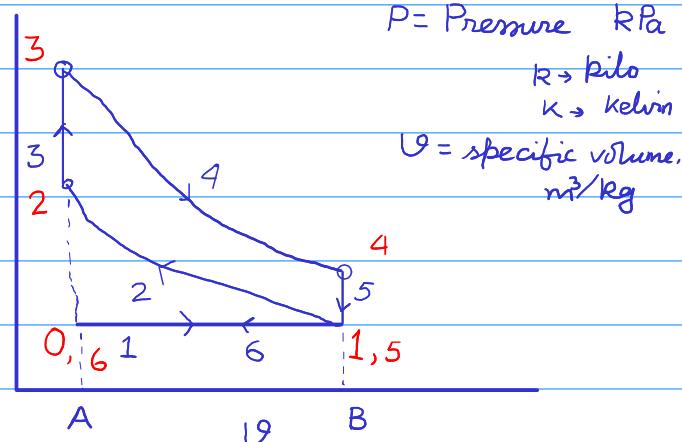
Volume is decreased. Compression

Temperature and pressure increases.

Process 3 Spark plug is on, fuel is combusted, chemical energy is released in the form of heat energy. Temperature and pressure increases.
 Piston doesn't move, i.e. at A

Process 4 Piston moves from A to B

Piston ↓ A-B



Process 5 EV opens. Piston is at B

Exhaust

Process 6 EV open, exhaust gas is pushed out

Piston ↑ B-A

Cycle: $\frac{\text{processes}}{1-2-3-4-5-6}$

$0-1-2-3-4-5-6$

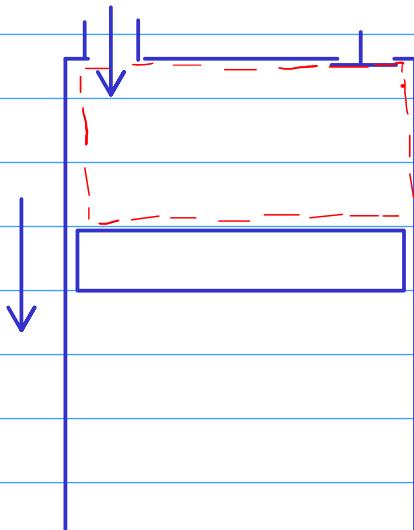
Process 1 starts

at 0,1 $P = P_{\text{atm}}$, $T = T_{\text{atm}}$

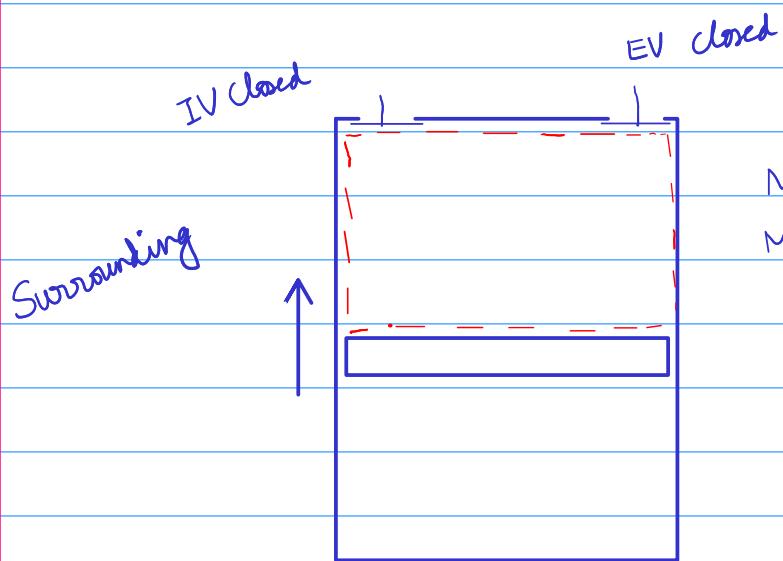
$$2 \quad P =$$

$r_c = \text{compression ratio}$

$$= \frac{v_1}{v_2} \quad 8 \sim 12 \text{ otto cycle SI engine}$$

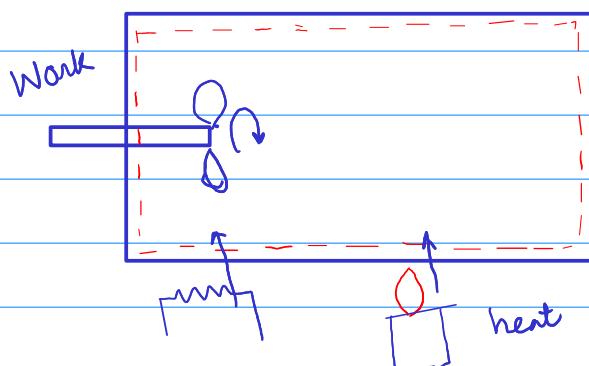


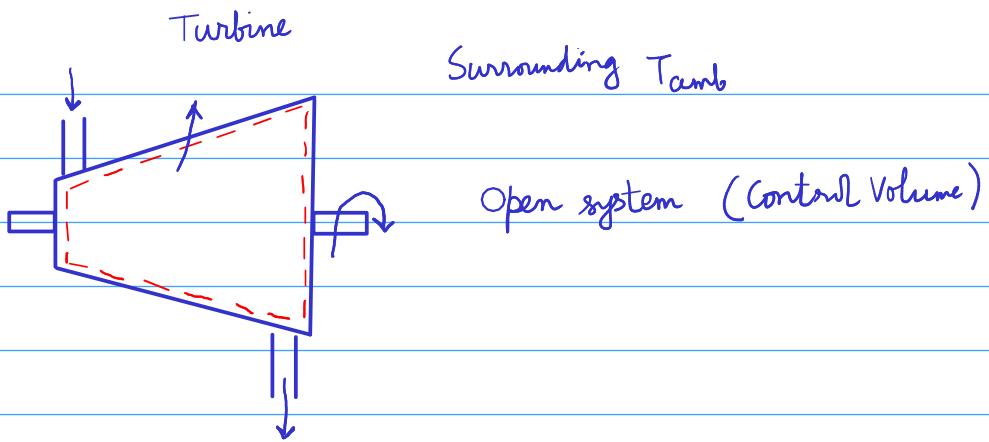
- - - System boundary
 mass is crossing the boundary
 control volume (cv)
 Open system



- - - Boundary
 Mass is not crossing the boundary
 Mass is fixed.
 Control mass system
 Closed system

Energy can cross the boundary
 Work or heat





K K

Ideal gas equation i.e. equation of state (EOS)

$$PV = n R_u T$$

R_u = Universal gas constant $8.314 \frac{RJ}{Kmole.K}$

n = number of kmol

T = Absolute scale K

V = Volume, m³

P = Pressure, kPa

$$R = \text{Gas constant} = \frac{R_u}{M}$$

M = Molecular mass $R_g / R_u M$

$$PV = n \times M \times \frac{R_u}{M} \times T$$

m = mass

$$PV = mRT$$

$= n \times M \text{ kg}$

$$R = \frac{R_u}{M}$$

V = Volume, m³

$\varrho = \text{specific volume } \frac{m^3}{kg}$

$$\frac{PV}{m} = RT$$

$$PV = RT$$

$$m_A = \frac{600 \times 0.5}{\frac{8.314 \times 293}{2}} = 0.248 \text{ kg}$$

$$m_B = \frac{150 \times 0.5}{\frac{8.314}{2} \times 303} = 0.060 \text{ kg}$$

$$P = 308 \times \frac{8.314}{2} \times 288/1 = 365.8 \text{ kPa}$$

Engine running on Otto Cycle, Iso-octane

$$V = 1200 \text{ cc}$$

$$\text{A/F ratio} = 15.12$$

$$P = 101 \text{ kPa}, T = 27^\circ\text{C}, M = 28.97 \text{ kg/kmol}, R = \frac{8.314}{28.97} \frac{\text{kg}}{\text{kgK}}$$

$$m_a = 0.0969 \text{ kg}$$

$$m_f = 0.006 \text{ kg}$$

last class

13/1/21

$$PV = mRT$$

$$P = 101 \text{ kPa}, V = 1200 \text{ cc} = 1200 \times 10^{-6} \text{ m}^3, m = ? \text{ kg}$$

$$101 \times 1200 \times 10^{-6}$$

$$R = \frac{8.314 \text{ kJ/kgmol.K}}{28.97 \text{ kg/kmol}}$$

$$M = 28.97 \text{ kg/kmol}$$

molecular mass of air

$$= m \times 0.287 \times 300$$

$$m = \frac{101 \times 1200 \times 10^{-6}}{0.287 \times 300}$$

$$= 0.287 \text{ kJ/kg.K}$$

$$T = 273 + 27 = 300 \text{ K}$$

$$= \frac{0.1212}{0.287 \times 300}$$

$$= 0.0014 \text{ kg} \checkmark \text{ For air}$$

$$\text{Mass of air. Mass of fuel} = \frac{0.0014}{15.12} = 0.0001 \text{ kg}$$

AIR STANDARD CYCLE

pure air.

Calorific value of gasoline or petrol = 44 MJ/kg

N = 3000 rpm, 4-stroke engine

Working medium is water. undergoes phase change.

solid phase

liquid phase

vapour phase

TURBINE

CONTROL MASS SYSTEM

CONTROL VOLUME

ISOLATED SYSTEM

Energy, mass
neither mass
nor energy can cross
the boundary

Inlet

①

Superheated steam

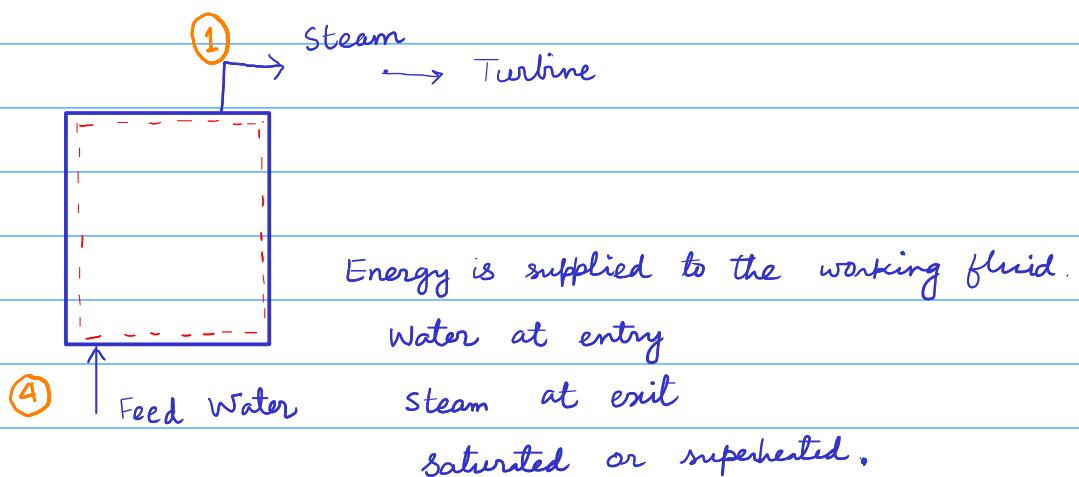
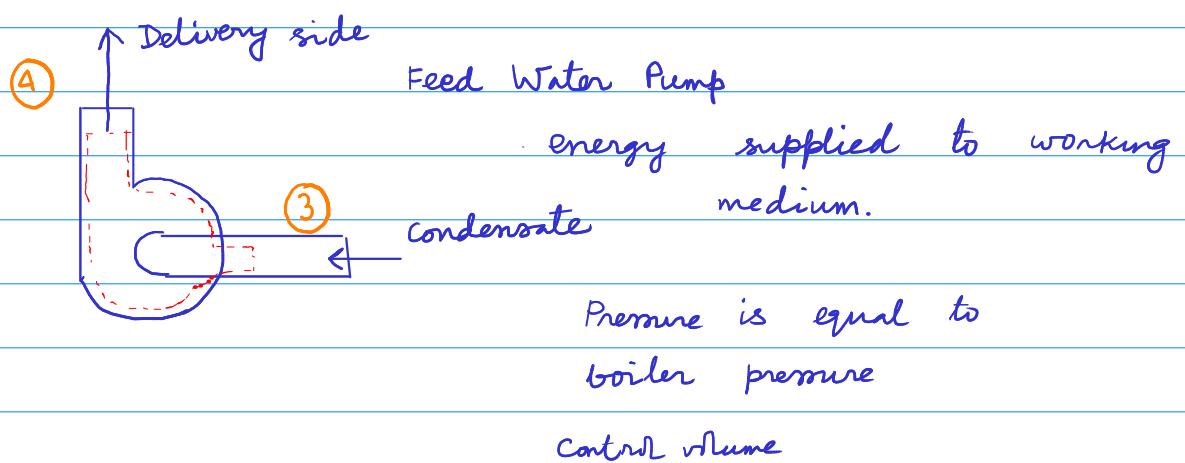
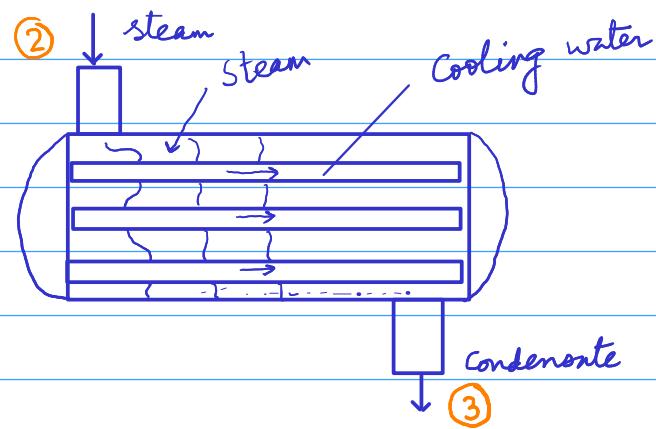
--- boundary

CONTROL VOLUME

② outlet

steam at saturated

wet steam

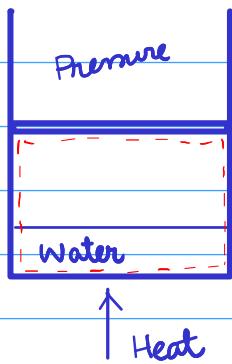


CYCLE IS COMPLETE

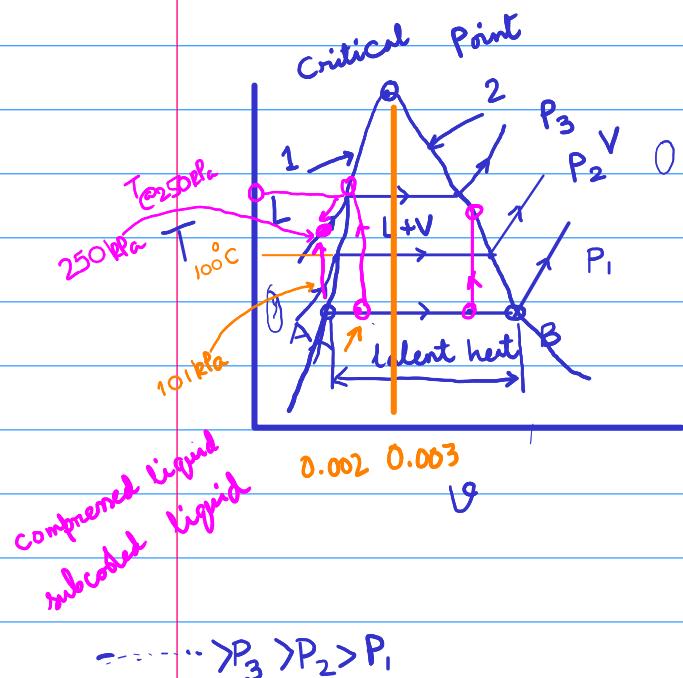
Process 1	Turbine	Work Produce
" 2	Condenser	Devices → Heat extraction
" 3	Feed Water Pump	→ Work consumption
" 4	Boiler	→ Heat addition

Property of water-vapour

~~14 | 1 | 2 |~~



- Temperature will keep on increasing.
 - Boiling will start; continue till all the water is converted to vapour phase. Temperature will remain same throughout this process. Latent heat of vaporization. $A \rightarrow B$
 - The temperature of steam will increase; we call it superheated steam.



y-axis = temperature, °C

x-axis vs specific volume, m^3/kg

A = location at saturated liquid, vapour = 0

B = location at " vapour, liquid = 0

Between A and B, mixture of liquid and vapour.

$$\begin{array}{lll} x = 0 & \text{at A} & \text{dryness fraction} \\ & & \\ x = 1 & \text{at B} & \text{quality of steam} \end{array}$$

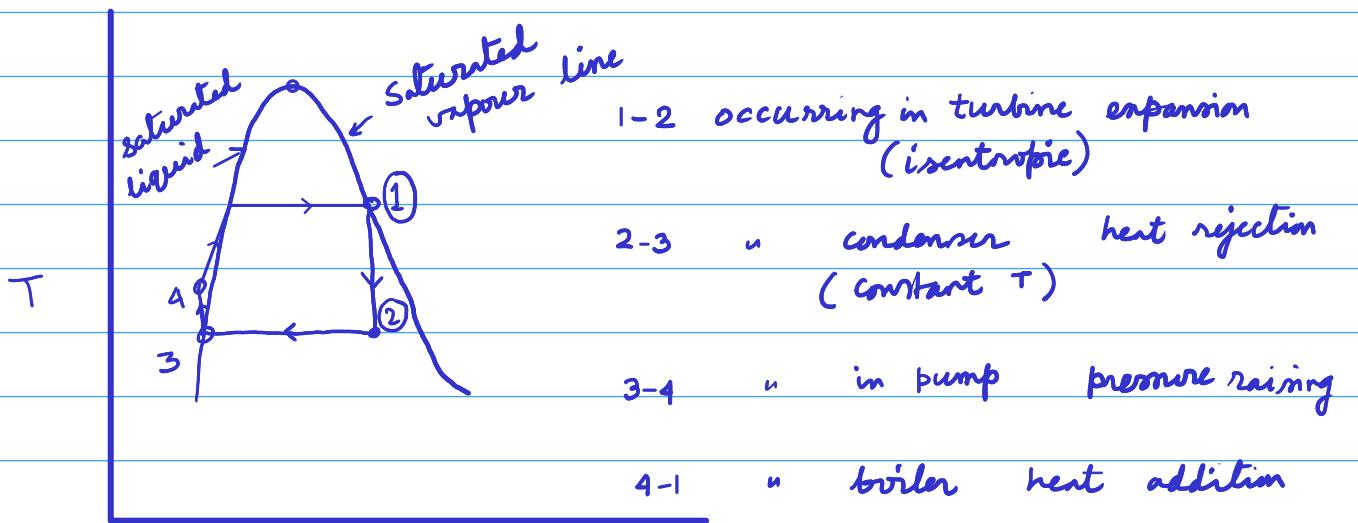
Vapour dome

$1 \rightarrow$ Saturated liquid line

2 → Saturated vapour line

Three thermodynamic property P, V, T

Enthalpy, internal energy, entropy are calculated using Maxwell's relation.



s

Rankine Cycle used in vapour power cycle.

15 | 1/2)

P = Pressure, kPa

T = Temperature, °C

v = specific volume, m³/kg

3-120

$$V = 4L, m = 2 \text{ kg}$$

$$v = \frac{4 \times 10^{-3}}{2} \text{ m}^3/\text{kg} = 0.002 \text{ m}^3/\text{kg}$$

50°C
saturated liquid-vapour

$$v_{cr} = 0.003106 \text{ m}^3/\text{kg}$$

$v < v_{cr}$, upon heating, the liquid-vapour mixture will be saturated liquid.

$$V = 400L,$$

$$v = \frac{400 \times 10^{-3}}{2} = 0.2 \text{ m}^3/\text{kg}$$

$v > v_{cr}$ upon heating, it will be saturated vapour

Work

Equilibrium:

Thermal

Mechanical

Chemical

1-state point 2Pa

2-state point

The process 1-2 is

carried in such a way that process 2-1 can be retraced without leaving any trace on the surrounding. Under this condition, we join all the intermediate points by a full line.

This is called a reversible process.

At state point 1, P_1, V_1, T_1

2, P_2, V_2, T_2

$$\delta W = PdV$$

Path function \rightarrow it

$\delta \rightarrow$ inexact differential

$d \rightarrow$ exact differential

$$\int_1^2 dV = V_2 - V_1$$

depends upon the path in which the process is carried out.

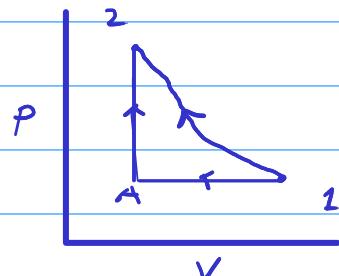
$$W_2 = \int_1^2 PdV$$

① Isothermal $PV = \text{constant}$

$$W_2 = \int_{V_1}^{V_2} \frac{\text{constant}}{V} dV$$

$$= \text{constant} \ln \frac{V_2}{V_1}$$

$$= P_1 V_1 \ln \frac{V_2}{V_1}$$



② Polytropic process $PV^n = \text{constant}$

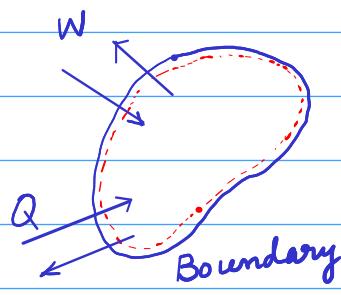
$$W_2 = \int_{V_1}^{V_2} PdV = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Energy balance

Sign convention

When heat energy is added to the system it is +ve.

Q coming out of the system, it is -ve



When work is done by the system, it is +ve
on u u .. -ve

Internal energy of the system = U

Energy of the system $E = U + \frac{1}{2}mv^2 + mgh$

Internal energy + kinetic energy + potential energy

$$E_{in} - E_{out} = \Delta E_{\text{system}}$$

$$Q - W = \Delta U \quad \text{neglecting K.E. and P.E.}$$

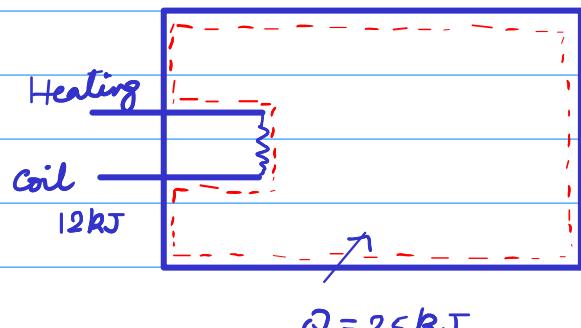
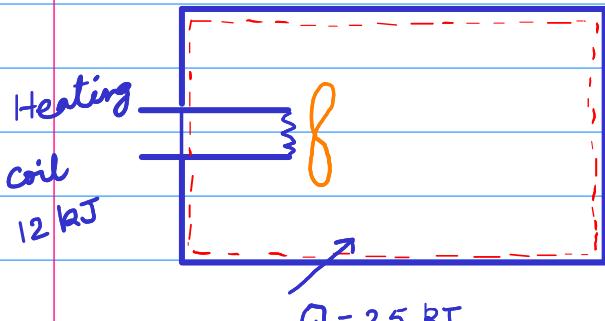
$$q_v = \frac{Q}{m} \text{ kJ/kg}$$

$$\omega = \frac{W}{m}$$

$$u = \frac{U}{m}$$

Extensive properties $Q, W, U, V,$

Intensive properties q, ω, u, v, p, T



$$Q - W = \Delta U$$

$$25 - (-12) = \Delta U$$

$$\Delta U = 25 + 12 = 37 \text{ kJ}$$

$$Q - W = \Delta U$$

$$25 + 12 - 0 = \Delta U$$

$$\Delta U = 37 \text{ kJ}$$

$$V_1 = 1200 \text{ cc}$$

$$\text{compression ratio} = 8.5 = \frac{V_1}{V_2}$$

$$T_1 = 27^\circ\text{C}$$

$$P_1 = 101 \text{ kPa}$$

Process is isentropic.

$$PV^\gamma = \text{constant}$$

$$\gamma = 1.4$$

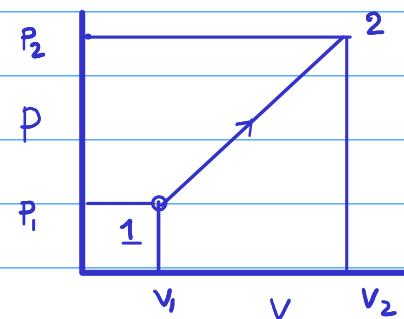
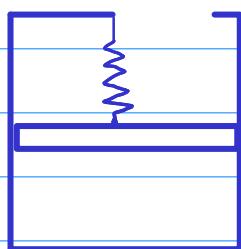
$$P_2, T_2, W_2$$

$$P_2 = 2020.73 \text{ kPa}$$

$$2020.73$$

$$T_2 = 706.13 \text{ K}$$

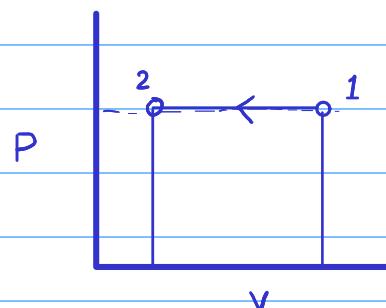
$$W_2 = -410 \text{ J}$$



$$W_2 = \frac{P_1 + P_2}{2} \times (V_2 - V_1)$$

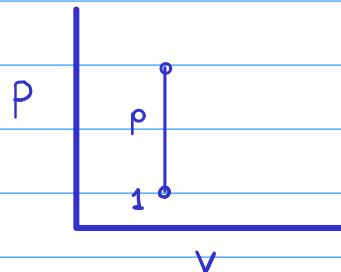
Constant pressure

$$W_2 = P_0 (V_2 - V_1)$$

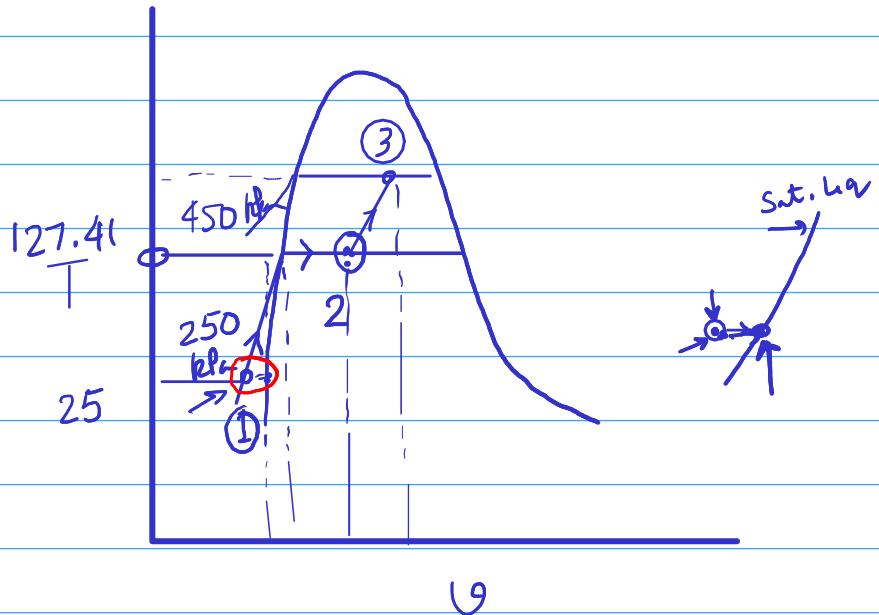


Constant volume

$$W_2 = 0$$



20/1/21



$$v_f @ 25^\circ C = 0.001003 \text{ m}^3/\text{kg}$$

$$v_f @ 250 \text{ kPa} = 0.001067 \text{ m}^3/\text{kg}$$

$$v_f @ 25^\circ C = 0.001003 \text{ m}^3/\text{kg}$$

$$V_1 = m \times v_f = 50 \times 0.001003 \text{ m}^3 = 0.05 \text{ m}^3$$

$$V_2 = 0.2 \text{ m}^3$$

$$V_3 = 0.2 + 0.1 \times 0.2 = 0.22 \text{ m}^3$$

$$v_2 = \frac{0.2}{50} < \frac{v_2}{m} = 0.004 \text{ m}^3/\text{kg} \quad v_f < v_2 < v_g \text{ at}$$

$$0.001003 < 0.004 < 0.71873$$

$$v_3 = \frac{0.22}{50} = 0.0044 \text{ m}^3/\text{kg}$$

$$v_2 = v_f + x(v_{fg})$$

$$x_2 = \checkmark$$

$$P_3 = P_2 + \frac{100(\text{kN/m}) \times 0.2(\text{m})}{0.1(\text{m}^2)} = 450 \text{ kPa}$$

$$v_3 = 0.0044 \text{ m}^3/\text{kg}$$

$$v_f = 0.001088 \text{ m}^3/\text{kg}$$

$$v_g = 0.41392 \text{ m}^3/\text{kg}$$

$$T_{sat} @ 450 \text{ kPa} = 147.9^\circ\text{C}$$

$$\text{W} = P_1 \times (V_2 - V_1) + \frac{P_2 + P_3}{2} \times (V_3 - V_2)$$

$$= 250 \text{ (kPa)} \times (0.2 - 0.05) \text{ m}^3 + \frac{250 + 450}{2} \times (0.22 - 0.2) \text{ kJ}$$

$$= +44.5 \text{ kJ}$$

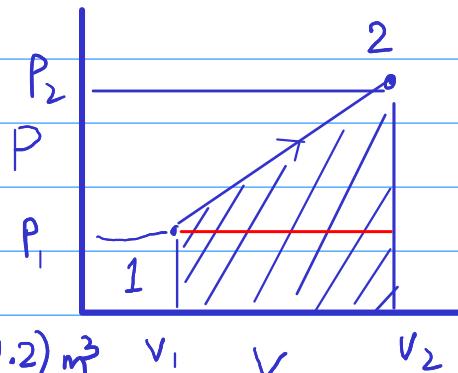
+ sign work is done by the system.
boundary work

21 | 1 | 21 4-114

$$W = \frac{P_2 + P_1}{2} \times (V_2 - V_1)$$

$$= \frac{800 + 200}{2} \text{ kPa} \times (0.5 - 0.2) \text{ m}^3$$

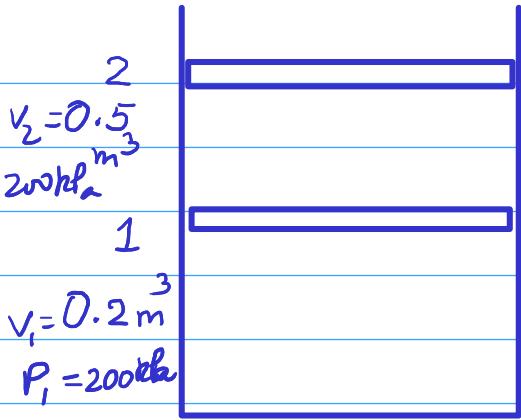
$$= 150 \text{ kJ}$$



$$P_1 = 200 \text{ kPa}$$

$$W_b, \text{ const pressure} = 200 \times (0.5 - 0.2) P_1 = 200 \text{ kPa}$$

$$= 60 \text{ kJ}$$



$$W_{b, \text{ spring}} = (150 - 60) \text{ kJ}$$

$$= 90 \text{ kJ}$$

4-36

$$V_1 = 5 \text{ L} = 5 \times 10^{-3} \text{ m}^3$$

$$v_f @ 175 \text{ kPa} = 0.001057 \text{ m}^3/\text{kg}$$

$$m = \frac{V_1}{v_f} = \frac{5 \times 10^{-3} \text{ m}^3}{0.001057 \text{ m}^3/\text{kg}}$$

$$= 4.731 \text{ kg}$$

$$W_p = -400 \text{ kJ}$$

$$W_b = P(V_2 - V_1) \quad W = W_p + W_b$$

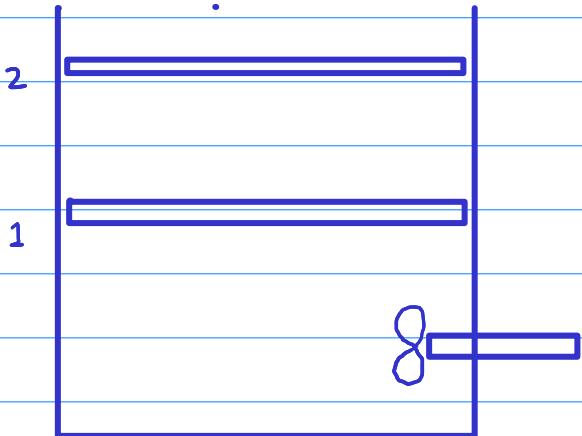
$$Q = +ve$$

$$Q - W = \Delta U$$

$$Q - (-400 + W_b) = U_2 - U_1$$

$$Q + 400 - P(V_2 - V_1) = U_2 - U_1$$

$$\begin{aligned} Q + 400 &= U_2 + P_2 V_2 - U_1 - P_1 V_1 \\ &= m h_2 - m h_1 \\ &= m (h_2 - h_1) \end{aligned}$$



$$H = U_2 + P_2 V_2 \quad \text{Extensive property}$$

$$H = \text{Enthalpy, kJ}$$

$$H = mh, h = \text{specific enthalpy, kJ/kg}$$

Intensive property

$$h_f = 487.01 \text{ kJ/kg}$$

$$h_2 = h_f + x h_{fg}$$

x = dryness fraction

$$= 0.5$$

$$= 487.01 + 0.5 \times 2213.1 \text{ kJ/kg}$$

$$= 1593.6 \text{ kJ/kg}$$

h_f = sp. enthalpy of saturated liquid =

h_g = vapour

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

$$Q + 400 = 4.731 \times (1593.6 - 487.01)$$

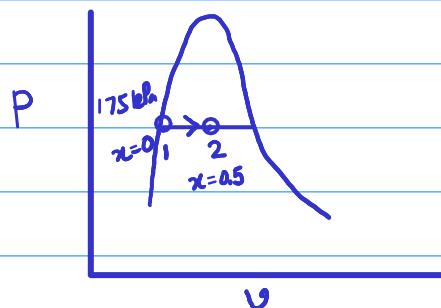
$$Q =$$

$$Q = V \times I \times t$$

$$I = 8A$$

$$t = 45 \text{ minutes} = 45 \times 60 \text{ seconds}$$

$$V = \text{volt}$$



$$\underline{\underline{22/1/21}} \quad 4-27 \quad m = 0.15 \text{ kg}$$

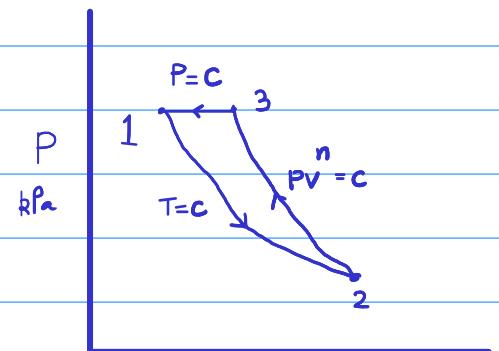
state 1

$$P_1 = 2 \text{ MPa} = 2000 \text{ kPa}$$

$$T_1 = 350^\circ\text{C} = (350 + 273) \text{ K} = 623 \text{ K}$$

state 1 \rightarrow 2 Isothermal process. $T_2 = 623 \text{ K}$

$$P_2 = 500 \text{ kPa}$$



state 2 \rightarrow 3 Polytropic compression process. $n = 1.2$

$$P_3 = 2000 \text{ kPa}$$

state 3 \rightarrow 1 constant pressure process.

R_u = Universal gas constant
= $8.314 \text{ kJ}/\text{mol}\cdot\text{K}$

$M = 28.97 \text{ kg}/\text{kmol}$

$R = R_u/M \text{ kJ}/\text{kg}\cdot\text{K}$

$$P_1 V_1 = m R T_1 \Rightarrow V_1 = \frac{0.15 \times 0.287 \times 623}{2000} \text{ m}^3 = 0.0134 \text{ m}^3$$

$$P_1 V_1 = P_2 V_2 \Rightarrow V_2 = \frac{P_1 V_1}{P_2} = \frac{2000 \times 0.0134}{500} = 0.0536 \text{ m}^3$$

$$P_2 V_2^n = P_3 V_3^n \Rightarrow 500 \times 0.0536^{1.2} = 2000 \times V_3^{1.2}$$

$$V_3^{1.2} = 0.00746 \Rightarrow V_3 = 0.0169 \text{ m}^3$$

$$W_2 = P_1 V_1 \ln \frac{V_2}{V_1} = 2000 \times 0.0134 \times \ln \frac{0.0536}{0.0134}$$

$$= 37.15 \text{ kJ}$$

$$W_3 = \frac{P_3 V_3 - P_2 V_2}{1-n} = \frac{2000 \times 0.0169 - 500 \times 0.0536}{1-1.2}$$

$$= - \frac{33.8 - 26.8}{0.2} = -35 \text{ kJ}$$

$$W_1 = P_1 (V_1 - V_3) = 2000 \times (0.0134 - 0.0169)$$

$$= -7 \text{ kJ}$$

$$W_{\text{net}} = W_2 + W_3 + W_1 = 37.15 - 35 - 7$$

$$= -4.85 \text{ kJ}$$

4-115

state 1

$$P_1 = 125 \text{ kPa}$$

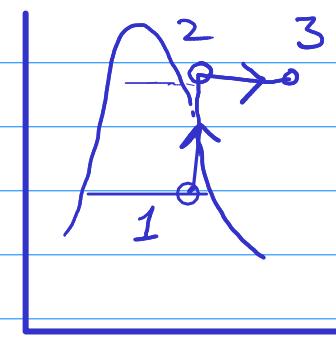
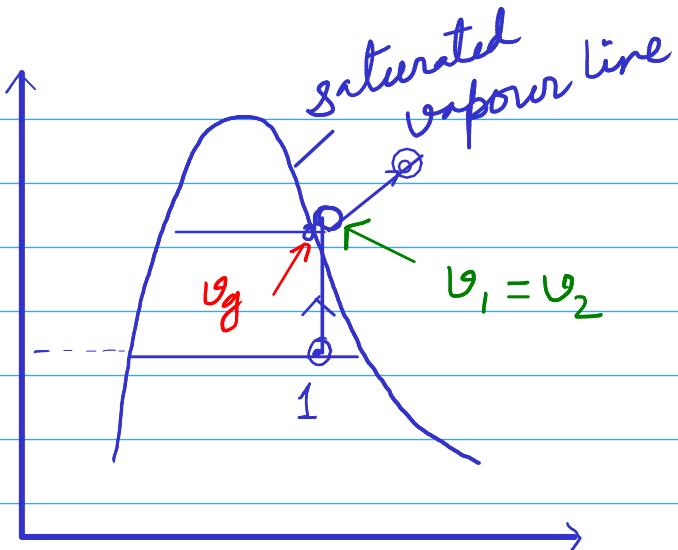
$$m = 5 \text{ kg}$$

$$m_c = 2 \text{ kg}$$

$$\begin{aligned} m_g &= m - m_c = (5 - 2) \text{ kg} \\ &= 3 \text{ kg} \end{aligned}$$

$$\text{dryness fraction } x = \frac{m_g}{m} = \frac{3}{5} = 0.6$$

$$T_{\text{sat}} @ P = 125 \text{ kPa} = 106^\circ \text{C} \quad 105.97^\circ \text{C}$$



$$v = v_f + x v_{fg}$$

$$v_f = 0.001048 \text{ m}^3/\text{kg}, \quad v_g = 1.3750 \text{ m}^3/\text{kg}$$

$$v_1 = 0.001048 + 0.6 \times (1.3750 - 0.001048)$$

$$= 0.8254 \text{ m}^3/\text{kg}$$

$$V_1 = m \times v = 5 \times 0.8254 \text{ m}^3 = 4.127 \text{ m}^3$$

state 2 $P_2 = 300 \text{ kPa}$

$$v_g = 0.60582 \text{ m}^3/\text{kg}$$

$$v_g < v_1$$

$$V_3 = 1.2 \times V_1 = 1.2 \times 4.127 = 4.9524 \text{ m}^3$$

$$\vartheta_3 = \frac{V_3}{m} = \frac{4.9524}{5} \text{ m}^3/\text{kg} = 0.99$$

$$\left. \begin{array}{l} P_3 = 300 \text{ kPa} \\ \vartheta_3 = 0.99 \text{ m}^3/\text{kg} \end{array} \right\} T_3 = 373.6^\circ\text{C}$$

$$\begin{aligned} W_{2+23} &= 0 + P_2(V_3 - V_2) \\ &= 300 \times (4.9524 - 4.127) \text{ kJ} \\ &= 247.62 \text{ kJ} \end{aligned}$$

+

'+' denotes that the boundary work is done by the system.

4-72

state 1

$$P_1 = 200 \text{ kPa},$$

$$T_1 = 27^\circ\text{C} = (273 + 27) \text{ K} = 300 \text{ K}$$

$$m = 3 \text{ kg}$$

$$P_1 V_1 = m R T_1$$

$$200 \times V_1 = 3 \times 0.287 \times 300$$

$$V_1 = 1.2915 \text{ m}^3$$

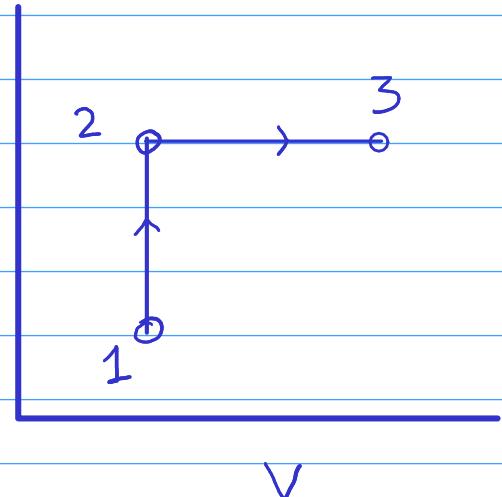
state 2

$$V_2 = 1.2915 = V_1$$

$$P_2 = 400 \text{ kPa}$$

$$P_2 V_2 = m R T_2$$

$$P_1 V_1 = m R T_1$$



$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \Rightarrow T_2 = T_1 \times \frac{P_2}{P_1}$$
$$= 300 \times \frac{400}{200}$$
$$= 600 \text{ K}$$

state 3

$$P_3 = 400 \text{ kPa}, = P_2$$

$$T_3 = 1200 \text{ K}$$

$$V_3 = 2 \times V_2 = 2 \times 1.2915 \text{ m}^3 = 2.583 \text{ m}^3$$

$$W = W_2 + W_3 = 0 + P_2(V_3 - V_2)$$

$$= 400 \times (2.583 - 1.2915) \text{ kJ}$$

$$= 516.6 \text{ kJ}$$

γ, c_p, c_v -----

$$Q - W = \Delta U = m c_V (T_3 - T_1)$$

$$c_V = 0.718 \text{ kJ/kg K}$$

$$Q = 3 \times 0.718 \times (1200 - 300) + 516.6$$

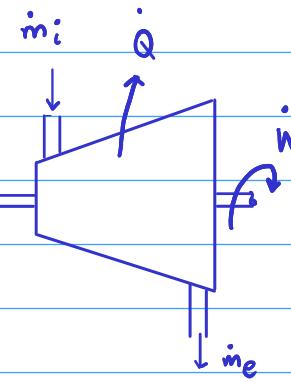
will be supplied.

$$= 1938.6 + 516.6 = 2455.2 \text{ kJ}$$

CONTROL VOLUME

⇒ Mass balance

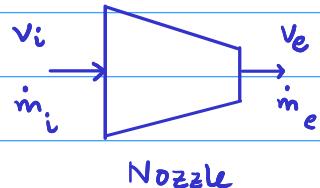
⇒ Energy balance



Reynolds Transport Theorem (RTT)

Turbine

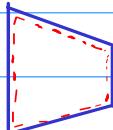
Steady Flow Energy Equation
(SFEET)



27/1/21

$$B_{\text{syst}} = m, m\vec{v}, m(u + \frac{v^2}{2} + gz)$$

$$\beta = \frac{dB_{\text{syst}}}{dm} = 1, \vec{v}, u + \frac{v^2}{2} + gz$$



Control volume

$$B_{\text{cv}} = \int_{\text{cv}} \beta P dV \quad V = \text{Volume}$$

$$\frac{dB_{\text{syst}}}{dt} = \frac{\partial B_{\text{cv}}}{\partial t} + (\text{Flux})_{\text{out}} - (\text{Flux})_{\text{in}}$$

Flux means property
that crosses a
boundary

$$B_{\text{syst}} = m ; \frac{dm}{dt} = \frac{d}{dt}(P \cdot 1 \cdot dV) + (m)_{\text{out}} - (m)_{\text{in}}$$

$$0 = \frac{d}{dt}(PdV) + (m)_{\text{out}} - (m)_{\text{in}}$$

$$\frac{d}{dt}(PdV) = (m)_{\text{in}} - (m)_{\text{out}}$$

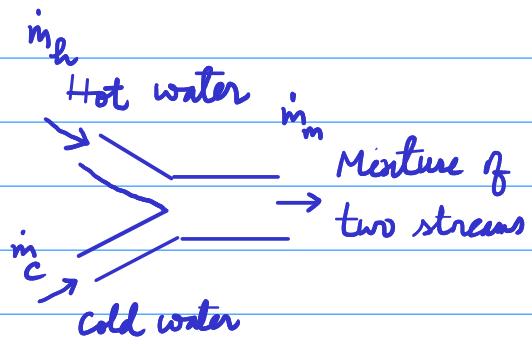
steady flow, $\frac{d}{dt}(PdV) = 0$

$$(m)_{\text{in}} = (m)_{\text{out}}$$

Mass conservation

$$\sum(m)_{\text{in}} = \sum(m)_{\text{out}}$$

$$m_h + m_c = m_m$$



Energy balance

$$B_{\text{synt}} = m(u + \frac{v^2}{2} + gz)$$

$$\beta = u + \frac{v^2}{2} + gz$$

$$\frac{dB_{\text{synt}}}{dt} = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV$$

$$+ (\text{Flux})_{\text{out}} - (\text{Flux})_{\text{in}}$$

$$(\text{Flux})_{\text{out}} = \dot{m}_e(u + \frac{v^2}{2} + gz)_e$$

$$(\text{Flux})_{\text{in}} = \dot{m}_i(u + \frac{v^2}{2} + gz)_i$$

$$\dot{Q} - (\dot{W} + (\dot{PV})_e - (\dot{PV})_i) = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV + \dot{m}_e(u + \frac{v^2}{2} + gz)_e - \dot{m}_i(u + \frac{v^2}{2} + gz)_i$$

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV + \dot{m}_e(u + Pv + \frac{v^2}{2} + gz)_e - \dot{m}_i(u + Pv + \frac{v^2}{2} + gz)_i$$

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV + \dot{m}_e(h + \frac{v^2}{2} + gz)_e - \dot{m}_i(h + \frac{v^2}{2} + gz)_i$$

Energy equation for control volume.

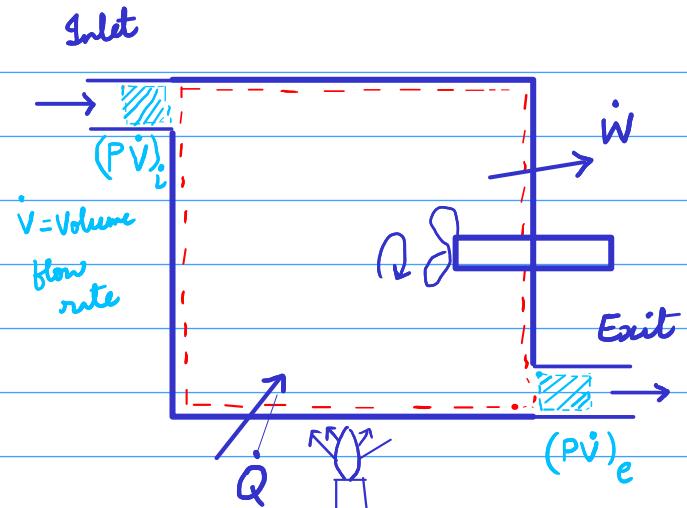
$$\sum \dot{Q} - \sum \dot{W} = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV + \sum \dot{m}_e(h + \frac{v^2}{2} + gz)_e - \sum \dot{m}_i(h + \frac{v^2}{2} + gz)_i$$

$$\frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV = 0, \text{ steady-state situation}$$

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_e(h + \frac{v^2}{2} + gz)_e - \sum \dot{m}_i(h + \frac{v^2}{2} + gz)_i$$

Steady Flow Energy Equation

SFEE



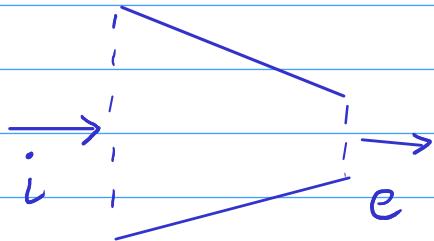
$X^0 K$
 $\checkmark K$

5-35

$$P_i = 600 \text{ kPa}$$

$$T_i = 500 \text{ K}$$

$$V_i = 120 \text{ m/s}$$



$$P_i = P_i R T_i$$

$$600 = P_i \times 0.287 \times 500$$

$$\rho_i = \frac{600}{0.287 \times 500} = 4.18 \text{ kg/m}^3$$

$$V_e = 380 \text{ m/s}$$

$$A_i = 2 A_e$$

Mass conservation equation, steady flow

$$\dot{m}_i = \dot{m}_e$$

$$P_i A_i V_i = P_e A_e V_e$$

$$4.18 \times 2 A_e \times 120 = P_e \times A_e \times 380$$

$$P_e = \frac{4.18 \times 2 \times 120}{380} = 2.64 \text{ kg/m}^3$$

SFEE

$$\dot{Q} - \dot{W} = \dot{m}_e \left(h + \frac{V^2}{2} + gz \right)_e - \dot{m}_i \left(h + \frac{V^2}{2} + gz \right)_i$$

adiabatic
no work

$$\dot{Q} = 0 \quad \dot{W} = 0 \quad \left(h + \frac{V^2}{2} + gz \right)_e = \left(h + \frac{V^2}{2} + gz \right)_i$$

$$\left(h + \frac{V^2}{2}\right)_e = \left(h + \frac{V^2}{2}\right)_i$$

$$h = CpT$$

C_p = specific heat at constant pressure

$$C_p T_e = C_p T_i + \frac{V_i^2 - V_e^2}{2}$$

$$C_p = 1005 \text{ J/kg.K}$$

$$T_e = T_i + \frac{V_i^2 - V_e^2}{2C_p}$$

$$= 500 + \frac{120^2 - 380^2}{2 \times 1005}$$

$$= 435.2 \text{ K}$$

(a)

$$P_e = P_e R T_e$$

$$= 2.64 \times 0.287 \times 435.2$$

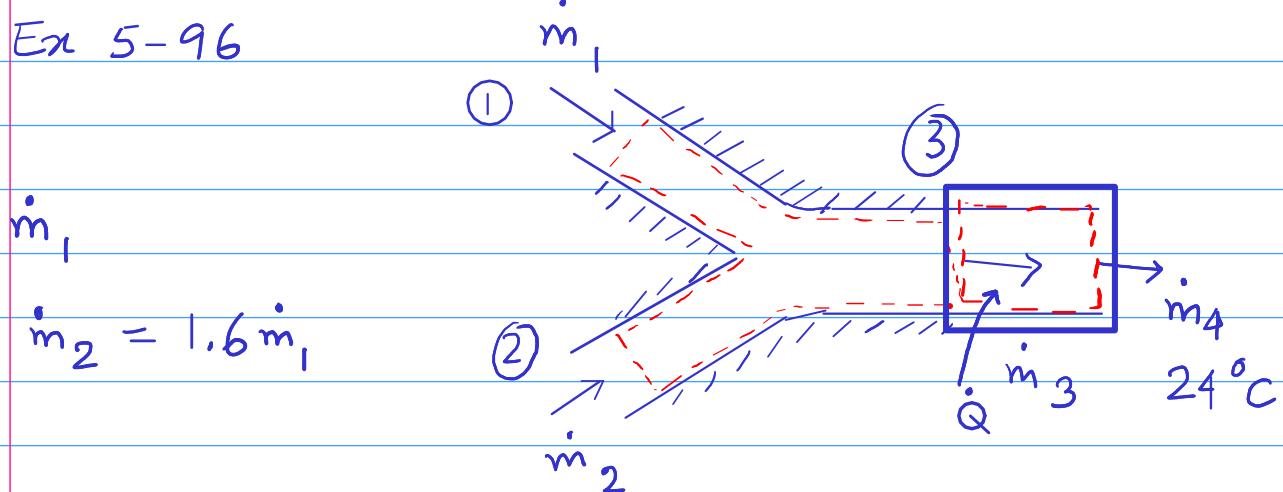
$$= 329.7 \text{ kPa}$$

(b)

Problem Set 02

28/1/21

Ex 5-96



Mass conservation. Assumption is steady flow.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

$$\dot{m}_1 + 1.6\dot{m}_1 = \dot{m}_3$$

$$\dot{m}_3 = 2.6\dot{m}_1$$

$$P_1 = 105 \text{ kPa}, T_1 = 5^\circ\text{C} = (273 + 5) \text{ K} = 278 \text{ K}$$

$$\dot{V}_1 = \text{Volume flow rate } \text{m}^3/\text{sec}$$

$$= 1.25 \text{ m}^3/\text{sec}$$

$$R = \text{Gas constant} = 0.287 \text{ kJ/kg K}$$

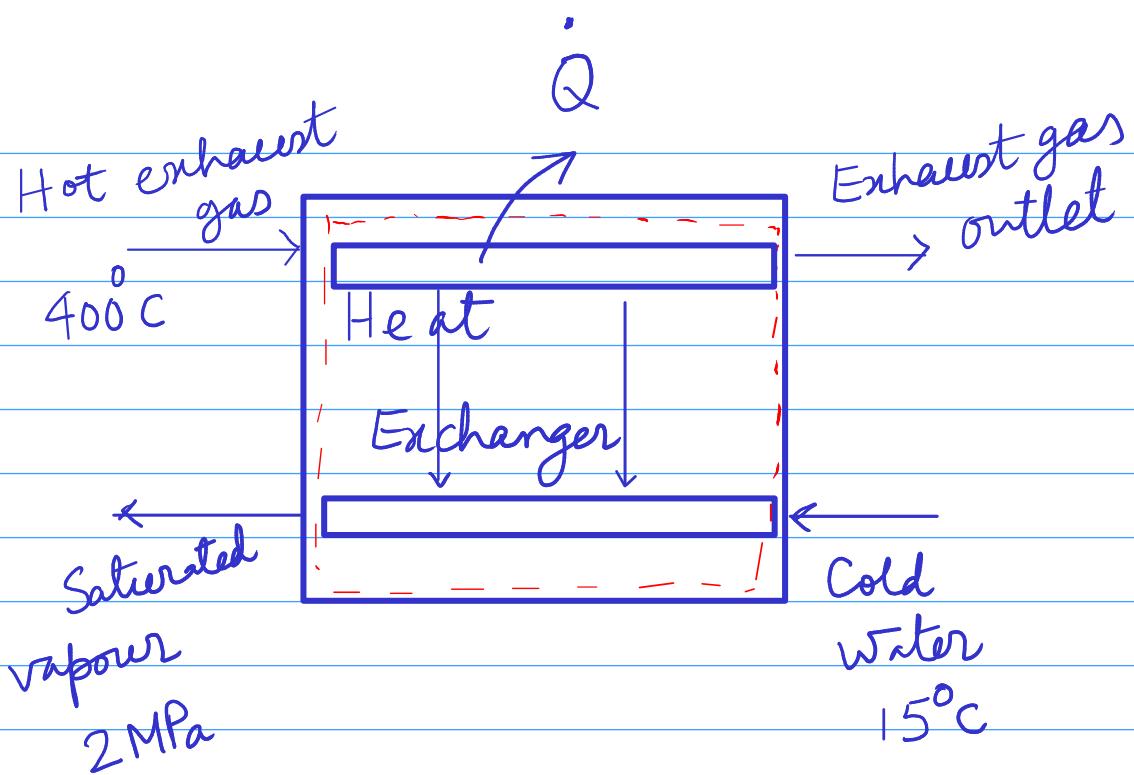
$$P_1 \dot{V}_1 = \dot{m}_1 R T_1$$

$$105 \times 1.25 = \dot{m}_1 \times 0.287 \times 278$$

$$\dot{m}_1 = 1.64 \text{ kg/sec}, \dot{m}_2 = 1.6 \times 1.64 \text{ kg/sec} = 2.624 \text{ kg/sec}$$

$$\dot{m}_3 = 2.6 \times 1.64 \text{ kg/sec} = 4.264 \text{ kg/sec}$$

~~5-97~~



$$\dot{m}_g = 32 \text{ kg/min} = \frac{32}{60} \text{ kg/sec} = 0.53 \text{ kg/sec}$$

$$\dot{m}_w = \frac{0.53}{15} \text{ kg/sec} = 0.035 \text{ kg/sec}$$

Energy balance:

S FEE

$$\dot{Q} - \dot{W} = \sum_e \dot{m}(h + \frac{V^2}{2} + gz) - \sum_i \dot{m}_i (h + \frac{V^2}{2} + gz)$$

$$\dot{W} = 0, \quad \dot{Q} = \dot{Q}_{\text{out}} = 0.1 \dot{Q}_{\text{exhaust}}$$

$$\sum \dot{m}_i (h + \frac{V^2}{2} + gz)_i = \dot{m}_g h_{gi} + \dot{m}_w h_{wi}$$

$$\sum \dot{m}_e (h + \frac{V^2}{2} + gz)_e = \dot{m}_g h_{ge} + \dot{m}_w h_{we}$$

$$-0.1 \dot{Q}_{\text{exhaust}} = \dot{m}_g h_{ge} + \dot{m}_w h_{we} - \dot{m}_g h_{gi} - \dot{m}_w h_{wi}$$

h_{wi} = Enthalpy of cold water at 15°C

$$= 62.982 \text{ kJ/kg}$$

h_{we} = Enthalpy of saturated vapour at 2 MPa

$$= 2798.3 \text{ kJ/kg}$$

$$C_p = 1.045 \text{ kJ/kg}\cdot\text{°C}$$

$h = C_p T$ for gas

$$T_{gi} = 400^\circ\text{C}, T_{ge} = ?$$

$$\dot{m}_g = \dot{m}_{ge} = \dot{m}_{gi} = 0.53 \text{ kg/sec}$$

$$\dot{m}_w = \dot{m}_{we} = \dot{m}_{wi} = 0.035 \text{ kg/sec}$$

$$-0.1 \times \dot{Q}_{enhuist} = \dot{m}_g \times C_p \times (T_{ge} - T_{gi}) + \dot{m}_w \times (2798.3 - 62.982)$$

$$\begin{aligned} -0.1 \times \dot{m}_g \times C_p \times (T_{ge} - T_{gi}) \\ = 0.53 \times 1.045 \times (T_{ge} - 400) + \\ 0.035 \times (2798.3 - 62.982) \end{aligned}$$

$$T_{ge} = 206.1^\circ\text{C} \quad (\text{a})$$

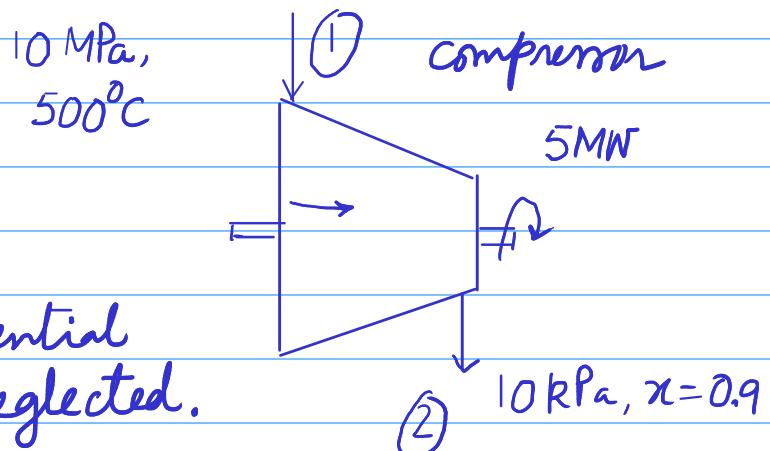
$$\dot{Q}_w = \dot{m}_w \times (h_{we} - h_{wi}) = 0.035 \times (2798.3 - 62.982) \text{ kJ/sec}$$

$$= 97.26 \text{ kW (b)}$$

5.51

$$\dot{m} = ? \text{ kg/s}$$

kinetic and potential energies are neglected.

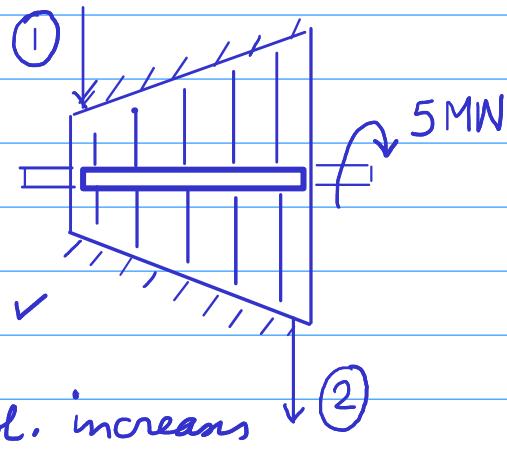


$$\begin{aligned} \dot{Q} - \dot{W} &= \dot{m}_2 \left(h_2 + \frac{V^2}{2} + gz_2 \right) - \\ &\quad \dot{m}_1 \left(h_1 + \frac{V^2}{2} + gz_1 \right), \end{aligned}$$

$$\begin{aligned} \dot{Q} &= 0, \quad \dot{W} = 5 \text{ MW} \\ &= 5000 \text{ kW} \end{aligned}$$

$$-\dot{W} = \dot{m}_2 h_2 - \dot{m}_1 h_1$$

sp. vol. increases as steam expands.



Energy equation

SFEE \rightarrow Steady Flow Energy Equation

$$\dot{Q} - \dot{W} = \sum \dot{m}_e (h + \frac{V^2}{2} + gz)_e - \sum \dot{m}_i (h + \frac{V^2}{2} + gz)_i$$

Insulated $\dot{Q} = 0, \dot{W} = 0$

$V = 0, z = 0$ because their contribution is negligible.

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$$

Assuming constant specific heat

$h = c_p T$ c_p = specific heat at constant pressure

T = Temperature K $(273 + 34)$
 \Downarrow

$$4.264 \times c_p \times T_3 = 1.64 \times c_p \times 278 + 2.624 \times c_p \times 307$$

$$T_3 = \frac{1.64 \times 278 + 2.624 \times 307}{4.264} = 295.85 \text{ K}$$

$$= 22.85^\circ\text{C}$$

For the conditioned room,

Mass conservation: $\dot{m}_3 = \dot{m}_4$

Energy conservation:

$$\dot{Q} - \dot{W} = \dot{m}_4 (h_4) - \dot{m}_3 (h_3)$$

$$c_p = 1.005 \text{ kJ/kg.K} = 4.264 \times 1.005 \times (24 - 22.85)$$

$$\text{K} \rightarrow \text{kilo}, \text{K} \rightarrow \text{kelvin} = 4.93 \text{ kJ/sec} = 4.93 \text{ kW}$$

Energy balance

$$\dot{Q} - \dot{W} = \frac{d}{dt} \dot{m} (u + \frac{V^2}{2} + gz) + \dot{m}_e (h + \frac{V^2}{2} + gz)_e - \dot{m}_i (h + \frac{V^2}{2} + gz)_i$$

$$Q - W = m_2 (u + \frac{V^2}{2} + gz)_2 - m_1 (u + \frac{V^2}{2} + gz)_1 + m_e (h + \frac{V^2}{2} + gz)_e - m_i (h + \frac{V^2}{2} + gz)_i$$

5-127

$$m_e = 0,$$

$$\dot{m}_i = m_2 - m_1$$

$$m_1 = \frac{P_1 V_1}{R T_1} = \frac{100 \times 2}{0.287 \times 295} \text{ kg} = 2.36 \text{ kg}$$

$$m_2 = \frac{600 \times 2}{0.287 \times (273 + 77)} = \frac{600 \times 2}{0.287 \times 350} = 11.95 \text{ kg}$$

$$\dot{m}_i = m_2 - m_1 = (11.95 - 2.36) \text{ kg} = 9.59 \text{ kg} \quad (\text{a})$$

$$\cancel{Q - W} = m_2 (u + \frac{V^2}{2} + gz)_2 - m_1 (u + \frac{V^2}{2} + gz)_1 + \cancel{m_e (h + \frac{V^2}{2} + gz)_e} - \cancel{m_i (h + \frac{V^2}{2} + gz)_i}$$

$W = 0$, K.E. and P.E. neglected, $m_e = 0$

$$Q = m_2 u_2 - m_1 u_1 - \dot{m}_i h_i$$

$$= 11.95 \times 0.718 \times 350$$

$$- 2.36 \times 0.718 \times 295$$

$$- 9.59 \times 1.005 \times 295$$

$$C_v = 0.718 \text{ kJ/kgK}$$

$$C_p = 1.005 \text{ kJ/kgK}$$

$$= -340 \text{ kJ} \quad (\text{b})$$

$$h_2 = h_f + x h_{fg}$$

$$= 191.81 + 0.9 \times 2392.1$$

$$= 2344.7 \text{ kJ/kg}$$

$$x = 0.9 \quad \text{Pressure } 10 \text{ kPa}$$

$$h_f = 191.81 \text{ kJ/kg}$$

$$h_{fg} = 2392.1 \text{ kJ/kg}$$

$$h_1 = 3375.1 \text{ kJ/kg} \quad 10 \text{ MPa} \quad T_{\text{sat}} = 311^\circ \text{C}$$

500°C superheated

$$h = 3375.1 \text{ kJ/kg}$$

$$-5000 = \dot{m}(2344.7 - 3375.1)$$

$$\dot{m}_1 = \dot{m}_2 = \dot{m} \text{ because}$$

single inlet and outlet

$$\dot{m} = \frac{5000}{3375.1 - 2344.7}$$

$$= 4.85 \text{ kg/sec}$$

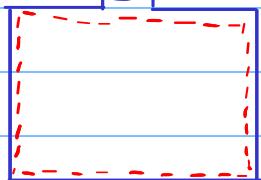
Unsteady Flow



Mass conservation equation

$$0 = \frac{dm_{cv}}{dt} + m_e - m_i$$

Filling time (charging)



Emptying time (discharging)

state 1 to state 2

Mass within the control volume at start of the process m_i ,
end m_2

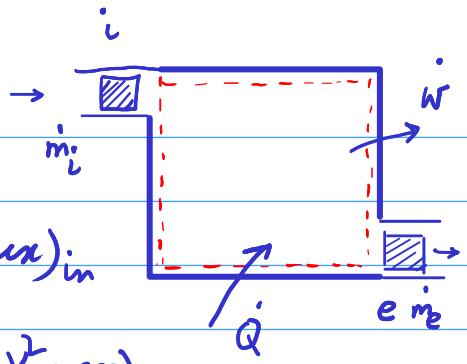
$$0 = (m_2 - m_i) + m_e - m_i$$

$$m_2 - m_i = m_i - m_e$$

4/2/21

RTT

$$\frac{dB_{\text{syst}}}{dt} = \frac{\partial}{\partial t} \int_C V \rho \beta dt + (\text{Flux})_{\text{out}} - (\text{Flux})_{\text{in}}$$



V = Volume

$$B_{\text{syst}} = m (u + \frac{v^2}{2} + gz)$$

$$\beta = \frac{dB_{\text{syst}}}{dm} = u + \frac{v^2}{2} + gz$$

$$\dot{Q} - (\dot{W}_i + \dot{W}_e) = \frac{d}{dt} \int_C V \rho (u + \frac{v^2}{2} + gz) dt + \dot{m}_e (u + \frac{v^2}{2} + gz)_e - \dot{m}_i (u + \frac{v^2}{2} + gz)_i$$

$$\dot{W}_e = P_e \dot{V}_e - P_i \dot{V}_i = \dot{m}_e P_e V_e - \dot{m}_i P_i V_i$$

$$\dot{Q} - \dot{W} - (\dot{m}_e P_e V_e - \dot{m}_i P_i V_i) = \frac{d}{dt} \int_C V \rho (u + \frac{v^2}{2} + gz) dt + \dot{m}_e (u + \frac{v^2}{2} + gz)_e - \dot{m}_i (u + \frac{v^2}{2} + gz)_i$$

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_C V \rho (u + \frac{v^2}{2} + gz) dt + \dot{m}_e (u + PV + \frac{v^2}{2} + gz)_e - \dot{m}_i (u + PV + \frac{v^2}{2} + gz)_i$$

Energy
Equation

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_C V \rho (u + \frac{v^2}{2} + gz) dt + \dot{m}_e (h + \frac{v^2}{2} + gz)_e - \dot{m}_i (h + \frac{v^2}{2} + gz)_i$$

Steady Flow: $\dot{Q} - \dot{W} = \dot{m}_e (h + \frac{v^2}{2} + gz)_e - \dot{m}_i (h + \frac{v^2}{2} + gz)_i$

Steady Flow Energy Equation (SFEE)

Mass conservation equation:

$$\frac{dm}{dt} = \frac{d}{dt} \int_C V \rho dt + \dot{m}_e - \dot{m}_i$$

$$\frac{d}{dt} \int_C V \rho dt + \dot{m}_e - \dot{m}_i = 0$$

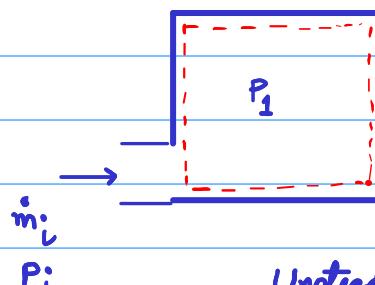
Steady Flow $\frac{d}{dt} \int_C V \rho dt = 0 \Rightarrow \dot{m}_e = \dot{m}_i \Rightarrow \sum \dot{m}_e = \sum \dot{m}_i$

Integrate between 1 and 2

$$m_2 - m_1 + \dot{m}_e - \dot{m}_i = 0 \quad m_e = \int_1^2 \dot{m}_e dt, \quad m_i = \int_1^2 \dot{m}_i dt$$

\dot{m}_i = mass flowrate at inlet

P_i = Pressure of the pipeline



Unsteady

P_1 = Pressure at the beginning of filling (charging process).

$P_2 = P_i$, filling or charging ends

Mass conservation
equation

$$m_2 - m_1 = m_i - m_e$$

$$\dot{Q} - \dot{W} = \frac{d}{dt} \int_{cv} p(u + \frac{V^2}{2} + gz) dt + m_e(h + \frac{V^2}{2} + gz)_e - m_i(h + \frac{V^2}{2} + gz)_i$$

Energy conservation equation

$$Q - W = m_2(u + \frac{V^2}{2} + gz)_2 - m_1(u + \frac{V^2}{2} + gz)_1 + m_e(h + \frac{V^2}{2} + gz)_e - m_i(h + \frac{V^2}{2} + gz)_i$$

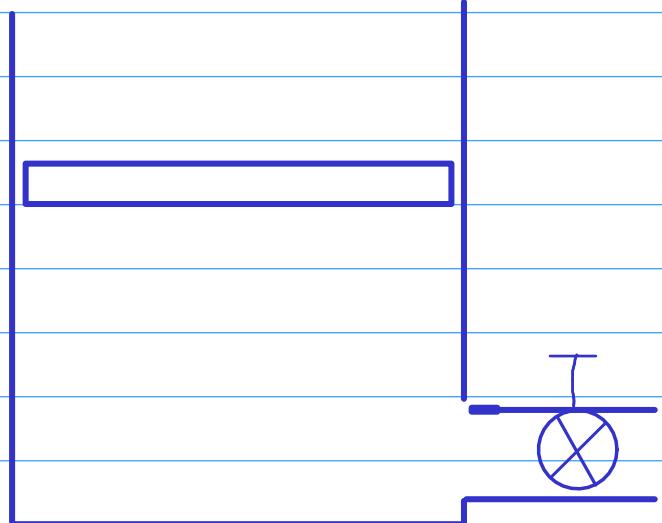
5-131 State 1

$$m_1 = 10 \text{ kg}$$

$$\chi = \frac{6 \text{ kg}}{10 \text{ kg}} = 0.6$$

Mass conservation

$$m_2 - m_1 = m_i - m_e$$



$$m_e = 0, \quad m_2 - m_1 = m_i$$

Energy conservation equation

K.E. and P.E. neglected

Insulated

$$Q - W = (m_2 u_2 - m_1 u_1) - m_i h_i$$

$$Q = 0$$

$$u_1 = u_f + \chi u_{fg}$$

$$P = 200 \text{ kPa}, \quad u_f = 504.5 \text{ kJ/kg}$$

$$= 504.5 + 0.6 \times 2024.6$$

$$u_{fg} = 2024.6 \text{ kJ/kg}$$

$$= 1719.26$$

$$u_2 = 2529.1 \text{ kJ/kg} = u_g \text{ (saturated vapour)}$$

$$h_1 = h_f + \chi h_{fg}$$

$$h_2 = 2706.3 \text{ kJ/kg} = h_g \text{ (saturated vapour)}$$

$$= 504.71 + 0.6 \times 2201.6$$

$$= 1825.67$$

$$h_i @ 0.5 \text{ MPa, } 35^\circ\text{C}$$

$$= 3168.1 \text{ kJ/kg}$$

$$- [P(V_2 - V_1)] = (m_2 u_2 - m_1 u_1) - m_i h_i$$

$$m_i h_i = m_2 u_2 - m_1 u_1 + m_2 P_2 V_2 - m_1 P_1 V_1$$

$$m_1 h_i = m_2(u_2 + p_2 v_2) - m_1(u_1 + p_1 v_1)$$

$$m_1 h_i = m_2 h_2 - m_1 h_1$$

$$(m_2 - m_1) h_i = m_2 h_2 - m_1 h_1$$

Unknown is m_2 .

5/2/21 $m_1 = 10 \text{ kg}, h_1 = 1825.67 \text{ kJ/kg}, h_2 = 2706.3 \text{ kJ/kg}, h_i = 3168.1 \text{ kJ/kg}$

$$(m_2 - 10) \times 3168.1 = m_2 \times 2706.3 - 10 \times 1825.67$$

$$m_2 \times (3168.1 - 2706.3) = 10 \times 3168.1 - 10 \times 1825.67$$

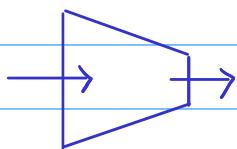
$$m_2 = \frac{3168.1 - 1825.67}{3168.1 - 2706.3}$$

$$= 29.07 \text{ kg}$$

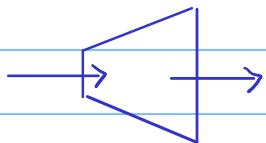
$$m_i = m_2 - m_1 = (29.07 - 10) \text{ kg} = 19.07 \text{ kg}$$

$$T_{sat} @ P = 200 \text{ kPa} = 120.2^\circ\text{C}$$

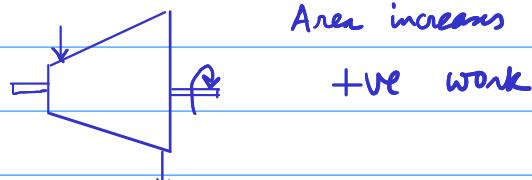
Nozzle



Diffuser

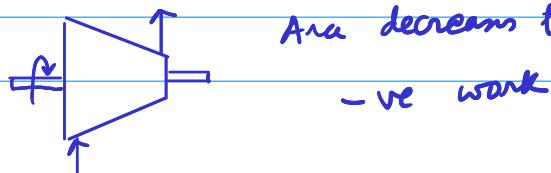


Turbine



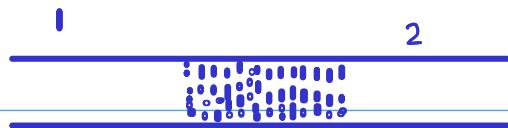
Area increases to accommodate increase specific volume.

Compressor



Area decreases to accommodate decrease in specific volume.

Throttling process



diameter comfort

$$\dot{Q} = \dot{W} = 0, \quad KE = 0, \quad PE = 0$$

$$h_2 = h_1$$

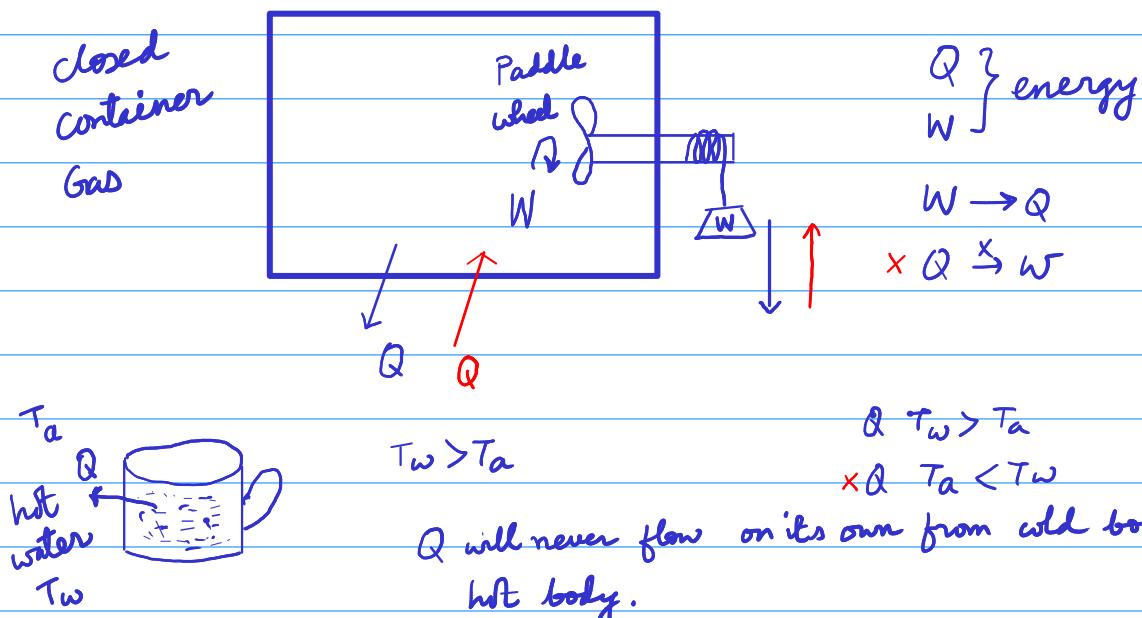
$$u_2 + p_2 v_2 = u_1 + p_1 v_1$$

Isoenthalpic process.

Charging or filling process

Discharging or emptying process

Second Law of Thermodynamics



Reservoir

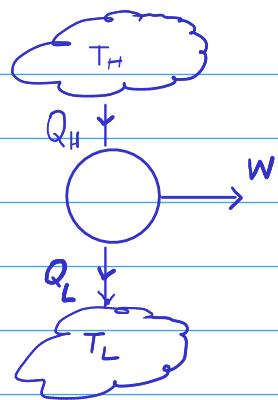
Heat If we added small quantity w.r.t. to the quantity in the reservoir

or we withdraw - - - - -

the temperature of the reservoir does not change.

Hot reservoir or high temperature reservoir (T_H)
 Cold " low " " " " (T_L)

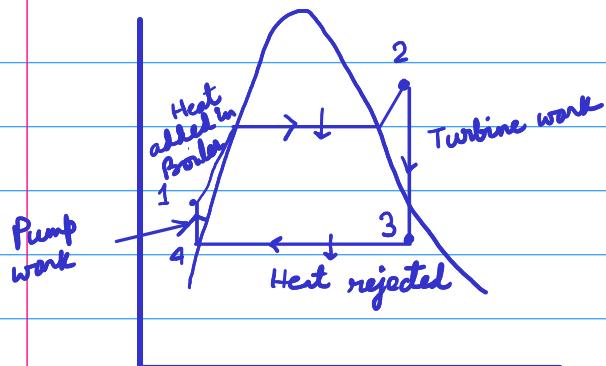
Device
Heat Engine
Petrol engine
Thermal power plant



A.C.

Q_H cannot be completely converted to work.

* We have to reject some heat to a low temperature reservoir.



Power plant cycle

$1 \rightarrow 2$ Q_H

$$W_{net} = Q_H - Q_L$$

$2 \rightarrow 3$

$$W_{net} = W + (-W_p)$$

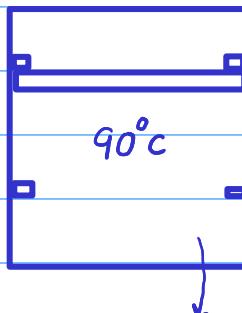
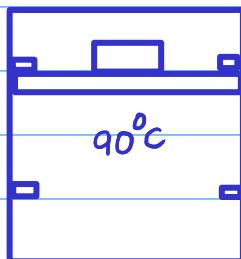
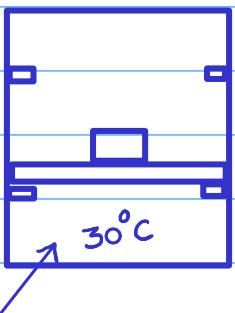
$3 \rightarrow 4$ Q_L

W_p becomes very large

$4 \rightarrow 1$

W_{net} decrease

Is it absolutely necessary to reject heat to low temperature reservoir?



100°C

Cycle where the initial condition 20°C has to be brought back by rejecting heat to the cold temperature reservoir
WASTE HEAT.

Objective \Rightarrow Convert heat into work.

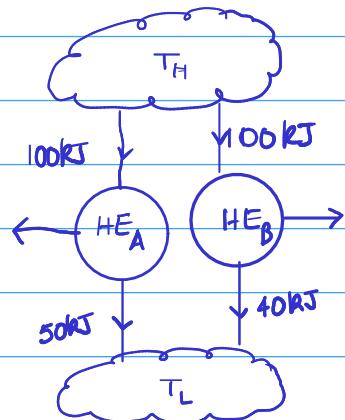
Q_H

W_{net}

$$\text{ratio} = \frac{W_{net}}{Q_H}$$

$$\text{Efficiency } \eta(\text{etc}) = \frac{W_{\text{net}}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

$$\eta = 1 - \frac{Q_L}{Q_H}$$



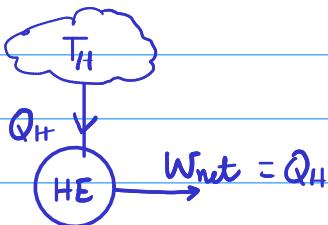
$$\eta_A = 1 - \frac{50}{100} = 0.5 = 50\%$$

$$\eta_B = 1 - \frac{40}{100} = 0.6 = 60\%$$

$$W_{\text{net}} = \eta Q_H$$

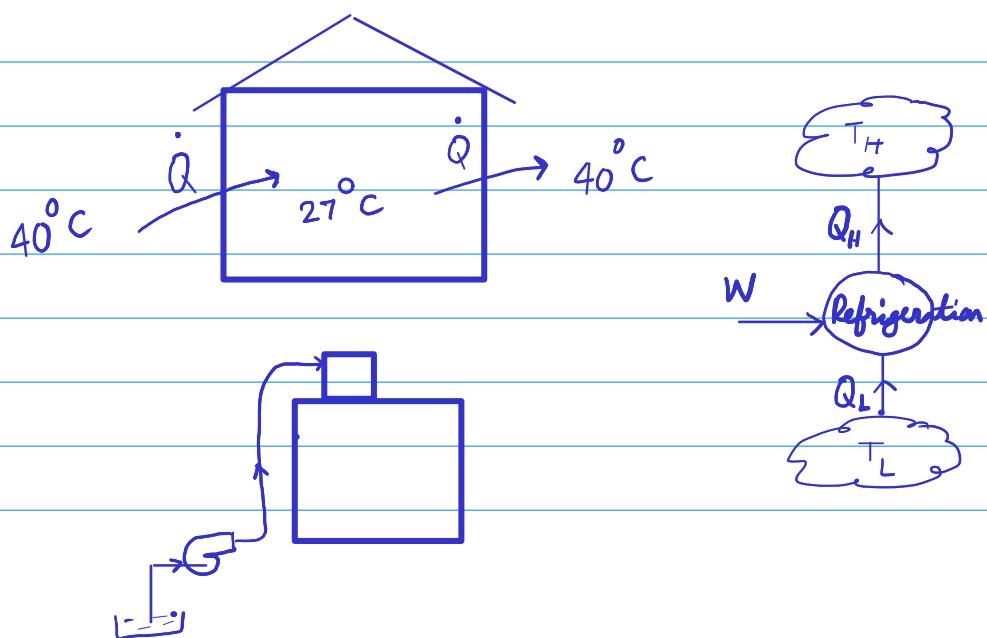
Work is a higher grade energy.

Heat is a lower grade energy.



Kelvin-Planck statement

It is impossible to construct a device that will run in a cycle and produce work exchanging heat with a single reservoir.

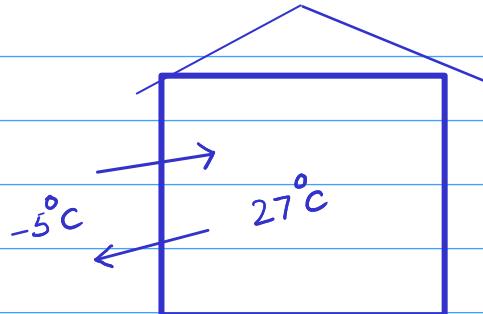
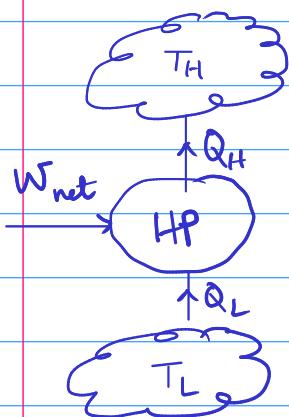


Desired objective Q_L

Energy to be supplied W

$$COP_{\text{refrigeration}} = \frac{Q_L}{W}$$

COP = Coefficient of performance



Desired objective = Q_H

Energy to be supplied = W_{net}

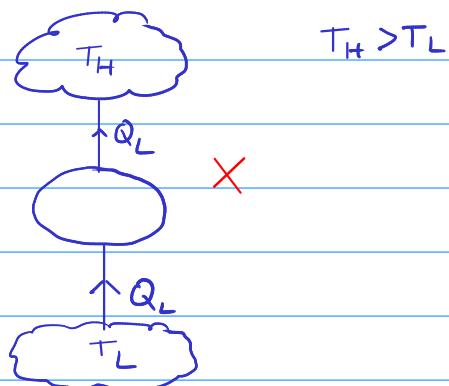
$$COP_{\text{HP}} = \frac{Q_H}{W_{\text{net}}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

$$W_{\text{net}} = Q_H - Q_L$$

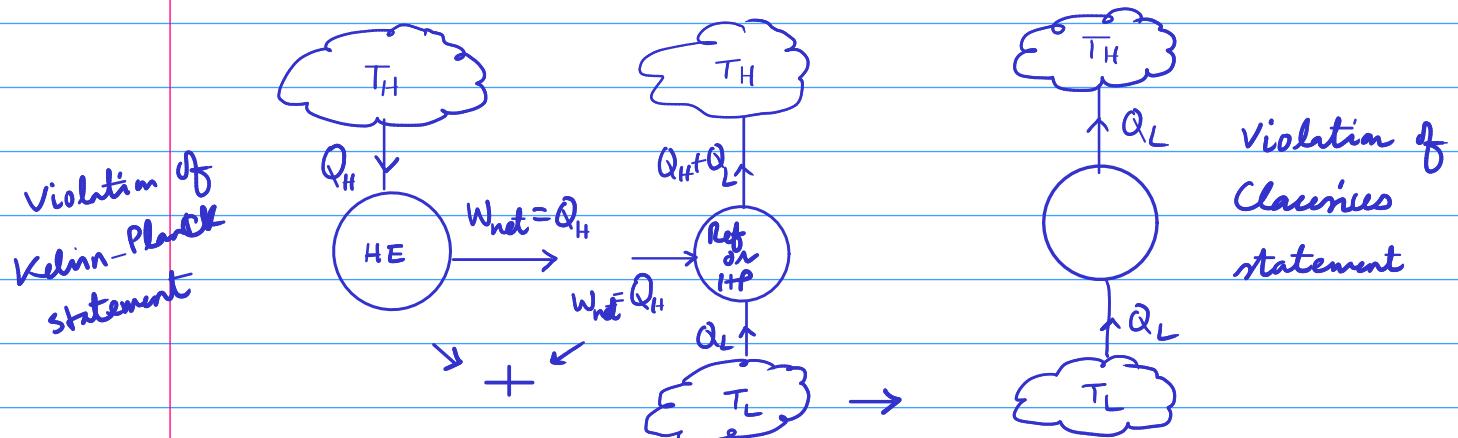
HP = Heat pump

Clairius statement

It is impossible to construct a device that operates in a cycle and produces no effect other than transfer of heat from a low-temperature body to a high-temperature body.

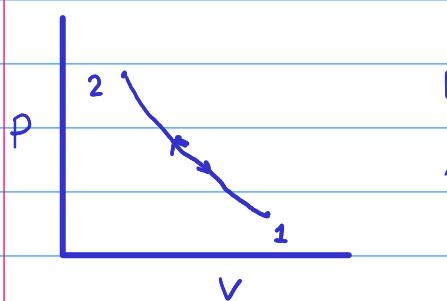


⇒ Violation of one statement leads to the violation of another statement.



The name of the cycle for which efficiency is maximum is called the Carnot Cycle.

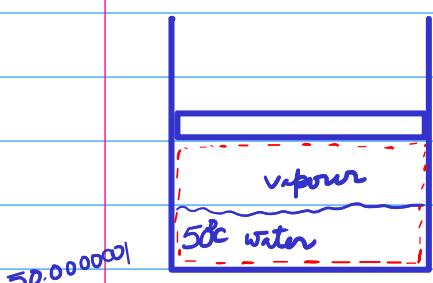
Why : Because all the processes are reversible process.



Process $1 \rightarrow 2$

Another process $2 \rightarrow 1$ which is reverse of Process $1 \rightarrow 2$

A reversible process leaves no trace on the surrounding when it is reversed.



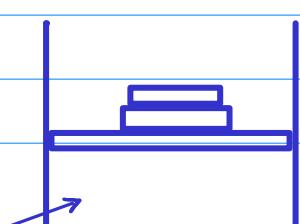
or infinitesimal small difference

Externally reversible

Internally reversible

{ Thermal

Equilibrium



Mechanical equilibrium

Chemical equilibrium.

Reversible Process

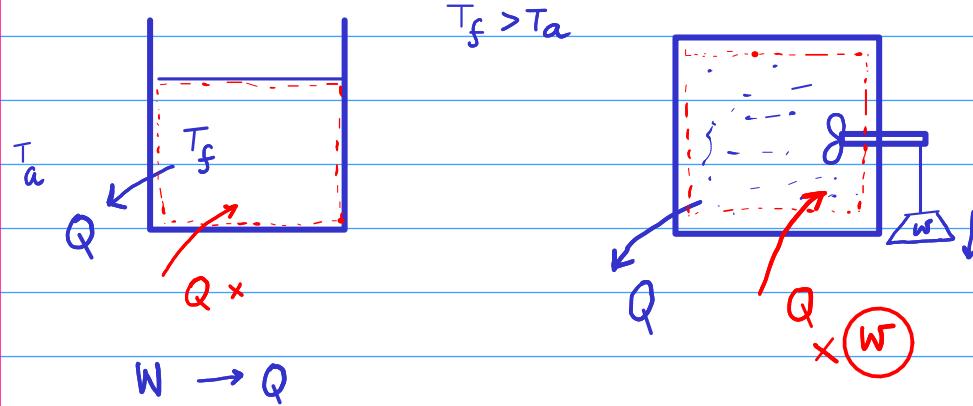
Thermodynamics: An engineering approach

Y.A. Cengel and M.A. Boles

McGraw Hill Education (I) Pvt. Ltd.

Seventh edition

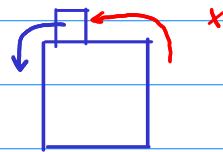
10/2/2021



$Q \rightarrow W$ without a mechanism or device

$$Q(T_f) \rightarrow Q(T_a) \quad T_f > T_a$$

$Q(T_f) \leftarrow Q(T_a)$ without a device



$Q \rightarrow W$

Kelvin-Planck statement which has not been disproved.
(Heat engine)

$$Q(T_a) \rightarrow Q(T_f)$$

Claudius statement

(Refrigeration or Heat Pump)



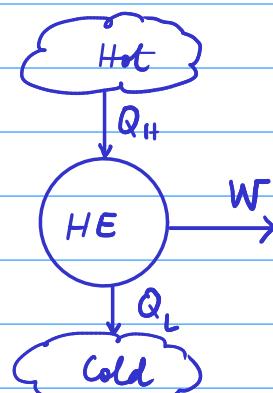
Heat engine \rightarrow Thermal Power Plant

Boiler

Turbine +ve

Condenser

Pump -ve



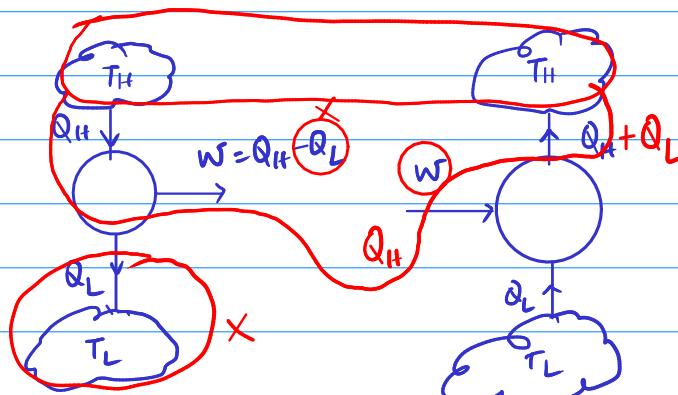
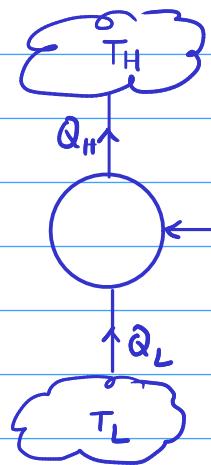
Reverse Heat engine

$Q_L \rightarrow$ Refrigeration

$Q_H \rightarrow$ Heat Pump

Clausius statement

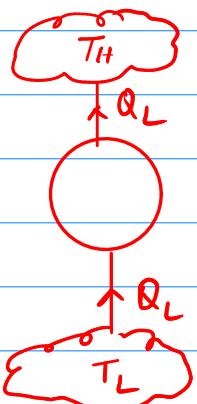
Violation of one statement leads to violation of other statement



$$W = Q_H - Q_L$$

$$Q_H = W + Q_L$$

Violation of
Clausius
statement

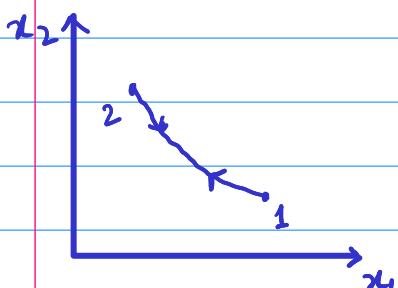


$$\eta_{th} = \frac{W_{net}}{Q_H} \quad \eta_{th} = \text{Thermal efficiency}$$

$$= \frac{Q_H - Q_L}{Q_H}$$

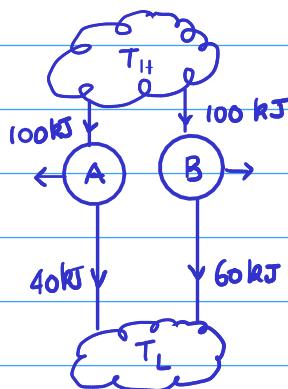
$$\boxed{\eta_{th} = 1 - \frac{Q_L}{Q_H}}$$

Reversible process when retraced will leave no changes (traces) in the surrounding.



$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

when is maximum?



$$\eta_{th,A} = 0.6 \quad 60\%$$

A better than B

$$\eta_{th,B} = 0.4 \quad 40\%$$

Reversible heat engine

Reversible processes

$$T_H = c$$

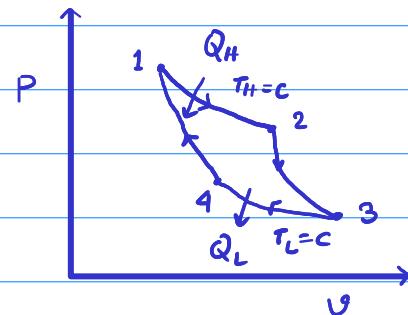
Carnot engine

$$s = c$$

Carnot cycle

$$T_L = c$$

$$s = c$$



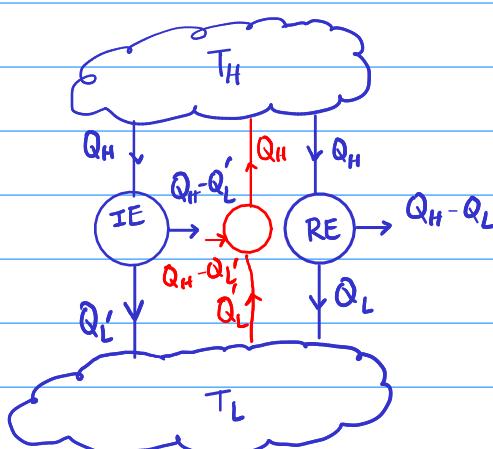
No engine can have thermal efficiency higher than the thermal efficiency of a Carnot engine (reversible engine).

$$\eta_{th,A} < \eta_{th,RE}$$

Possible

$$\eta_{th,A} > \eta_{th,RE}$$

Not possible.



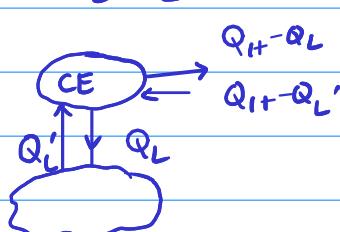
$$\eta_{IE} > \eta_{RE}$$

$$Q_H - Q_L' > Q_H - Q_L$$

$$Q_L - Q_L'$$

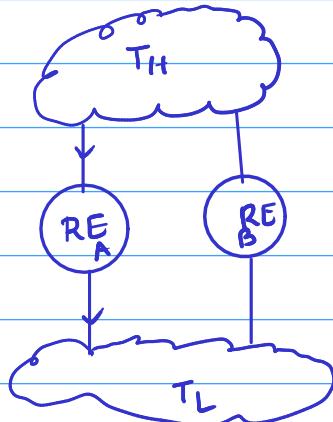
$$Q_L' < Q_L$$

$$Q_{IE} - Q_L' = Q_H + Q_L$$



Not Possible.
violates Kelvin-Planck statement

$$\eta_{th, IE} < \eta_{th, RE}$$



$$\eta_{th, RE_A} = \eta_{th, RE_B}$$

Efficiency of all reversible engines

between the same two reservoirs

is same. Reversible engine efficiency is independent of working fluid.

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

$T \rightarrow$ Absolute temperature, K

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

equally applicable to reversible and irreversible cycle.

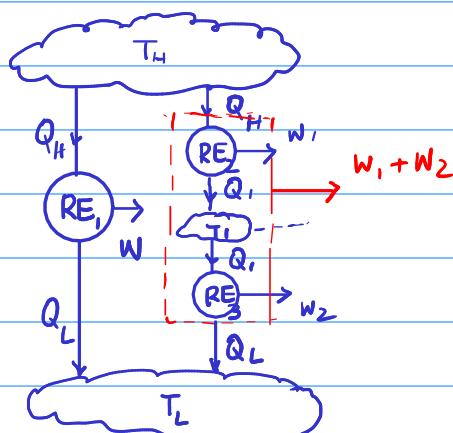
$$= 1 - \frac{T_L}{T_H} \quad \text{cycle is reversible only.}$$

17/2/21

$$\eta_{th, RE} = 1 - \frac{Q_L}{Q_H}$$

$$\eta_{th, RE} \neq f(\text{working fluid}) \quad \eta_{th, RE} = g(T_H, T_L)$$

$$\frac{Q_H}{Q_L} = f(T_H, T_L)$$



$$RE_1 \quad \frac{Q_H}{Q_L} = f(T_H, T_L)$$

$$RE_2 \quad \frac{Q_H}{Q_I} = f(T_H, T_I)$$

$$RE_3 \quad \frac{Q_I}{Q_L} = f(T_I, T_L)$$

$$\frac{Q_H}{Q_L} = f(T_H, T_L)$$

$$\frac{Q_H}{Q_L} \times \frac{Q_I}{Q_L} = f(T_H, T_I) \times f(T_I, T_L) = f(T_H, T_L)$$

$$= \frac{\phi(T_H)}{\phi(T_I)} \times \frac{\phi(T_I)}{\phi(T_L)} = \frac{\phi(T_H)}{\phi(T_L)}$$

Lord Kelvin proposed $\phi(T) = T$ $T = \text{Absolute temperature}$
 $= \text{Kelvin scale}$

$$\eta_{th} = 1 - \frac{Q_L}{\dot{Q}_H}$$

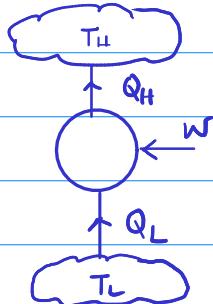
Equally holds good whether the cycle is reversible or irreversible.

$$\eta_{th, RE} = 1 - \frac{T_L}{T_H}$$

$\frac{Q_L}{\dot{Q}_H} = \frac{T_L}{T_H}$ only when the cycle is reversible

$$COP_R = \frac{Q_L}{W} = \frac{Q_L}{\dot{Q}_H - Q_L} = \frac{1}{\frac{\dot{Q}_H}{Q_L} - 1} = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{T_L}{T_H - T_L}$$

R = Refrigeration cycle



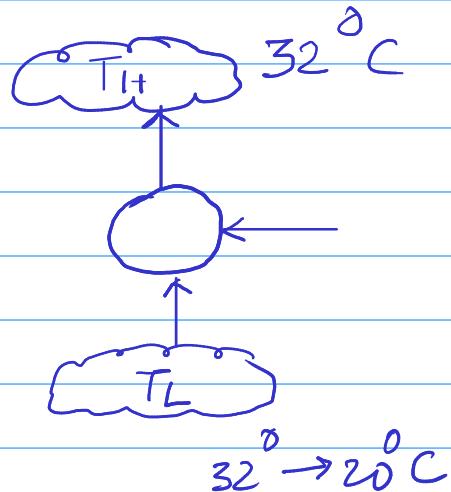
HP = Heat pump

$$COP_{HP} = \frac{Q_H}{W} = \frac{Q_H}{\dot{Q}_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}} = \frac{1}{1 - \frac{T_L}{T_H}} = \frac{T_H}{T_H - T_L}$$

$$COP_{HP} = \frac{Q_H}{\dot{Q}_H - Q_L} = \frac{Q_H - Q_L + Q_L}{\dot{Q}_H - Q_L} = \frac{Q_H - Q_L}{\dot{Q}_H - Q_L} + \frac{Q_L}{\dot{Q}_H - Q_L} = 1 + \frac{Q_L}{\dot{Q}_H - Q_L} = 1 + COP_R$$

6-44 $T_H = \text{surrounding}$

$$= 273 + 32 = 305 \text{ K}$$



$T_L = \text{Inside temperature}$
 desired

$$= 273 + 20 = 293 \text{ K}$$

$$Q_L = m_{\text{entire}} \times c_v \times (T_H - T_L)$$

$$COP_R = \frac{293}{12}$$

$$= 800 \times 0.72 \times (32 - 20) \text{ kJ} = 24.41$$

$$= 6912 \text{ kJ}$$

$$COP_R = \frac{Q_L}{W_{in}} \quad W_{in} = \frac{Q_L}{COP_R} = \frac{6912}{2.5} = 2764.8 \text{ kJ}$$

$$\dot{W}_{in} = \text{Power} = \frac{2764.8}{15 \times 60} \text{ kW} = 3.072 \text{ kW}$$

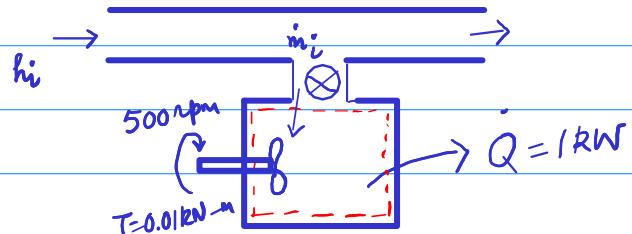
18/2/2021

$$\dot{m}_i = 0.1143 \text{ kg/s}$$

$$h_i = 3069.26 \text{ kJ/kg}$$

$$\text{at any instant } \dot{m}_{av} = 2 \text{ kg}$$

$$u_{av} = 2510 \text{ kJ/kg}$$



a) Determine power output

b) Rate of change of total internal energy

c) Specific internal energy of the system.

Neglect KE and PE at inlet.

$$\dot{Q} - \dot{W} = \frac{d}{dt} (\dot{m}_w u_w) + \dot{m}_e h_e - \dot{m}_i h_i$$

$$\dot{m}_e = 0,$$

$$\omega = \frac{2\pi N}{60}$$

$$\dot{Q} = -1 \text{ kW}; \dot{W} = -\omega T$$

$$a) \dot{W} = -\omega T \text{ kW}$$

$$b) \frac{d}{dt} (\dot{m}_w u_w) = \dot{Q} - \dot{W} + \dot{m}_i h_i$$

$$c) \frac{d}{dt} (\dot{m}_w u_w) = \dot{m}_w \frac{du_w}{dt} + u_w \frac{dm_w}{dt}$$

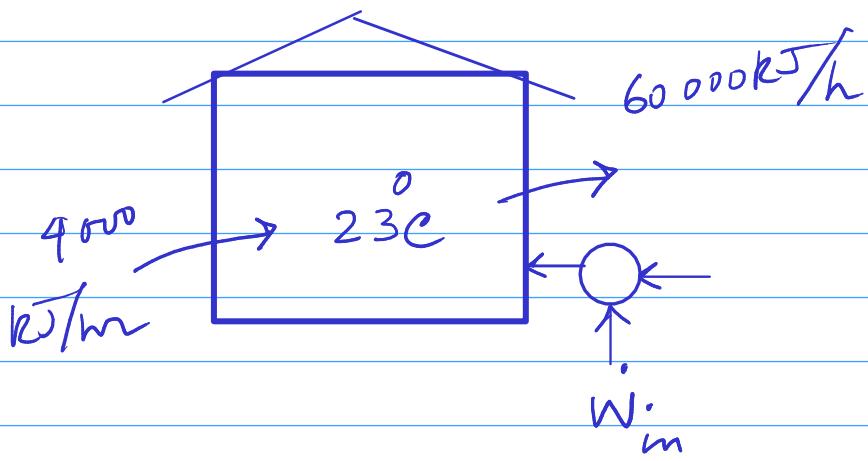
$$\dot{m}_w = 2 \text{ kg}, \quad \frac{dm_w}{dt} = 0.1143 \text{ kg/s}, \quad u_{av} = 2510 \text{ kJ/kg}$$

$$\frac{d}{dt} (\dot{m}_w u_w) = \dot{m}_w \frac{du_w}{dt} + u_w \frac{dm_w}{dt} \Rightarrow \frac{du_w}{dt} = ? \text{ kJ/kg-s}$$

Tomorrow, you give me the solution to this problem

6-51

$$COP = \frac{\dot{Q}_H}{\dot{W}}$$

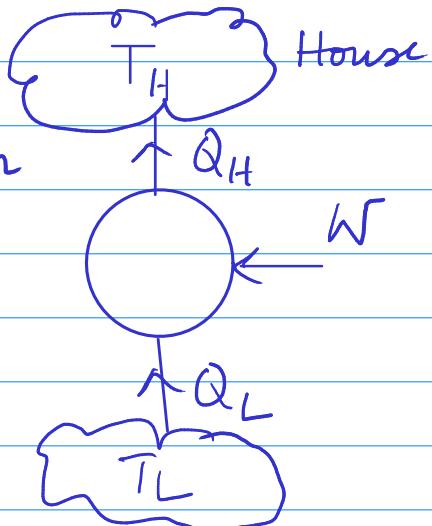


$$\dot{W} = \frac{\dot{Q}_H}{COP}$$

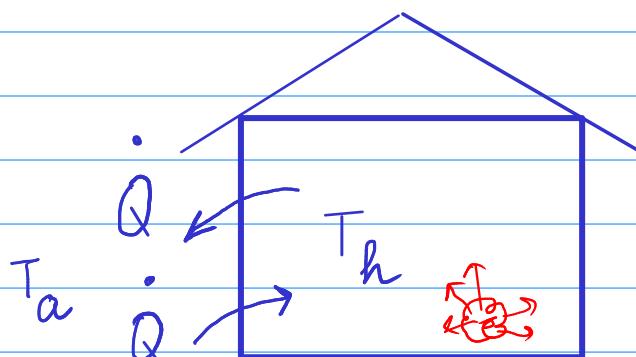
$$\dot{Q}_H = (60000 - 4000) \text{ kJ/h}$$

$$= \frac{56000}{36000} \text{ kJ/s}$$

$$= \frac{140}{9} \text{ kJ/s}$$



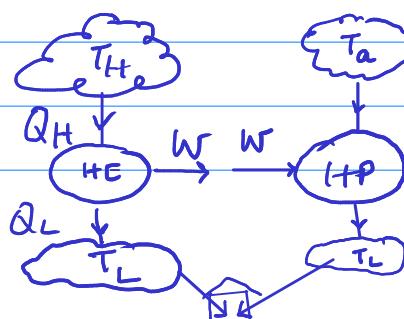
$$\dot{W} = \frac{140}{9 \times 2.5} = \frac{56}{9} \text{ kW} = 6.22 \text{ kW}$$



T_h = Temperature of house

T_a = Temperature of ambient surroundings
 $T_h > T_a$

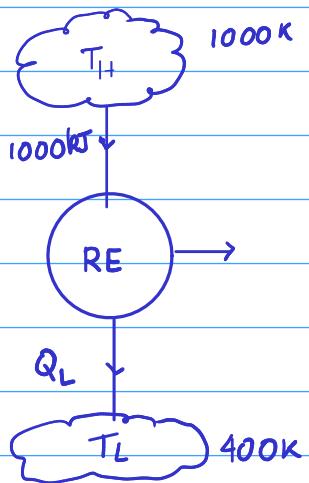
$$\dot{Q} = m \times CV$$



$$T_h = 27^\circ C \quad T_H = 300^\circ C$$

$$T_a = -5^\circ C$$

$$T_L = T_h$$



$$T_H = 1000 \text{ K}$$

$$Q_H = 1000 \text{ kJ}$$

$$T_L = 400 \text{ K}$$

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

$$\eta_{th,RE} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}; \quad \frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

$$Q_L = 400 \text{ kJ} \text{ remains}$$

$= 450, 500, 550 \checkmark$

$50, 100, 150 \text{ kJ}$

$$Q_L = Q_H \times \frac{T_L}{T_H} = 1000 \times \frac{400}{1000} = 400 \text{ kJ}$$

$$Q_L = 450 \text{ kJ}$$

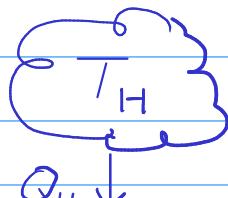
$$\eta_{th,RE} = 1 - \frac{T_L}{T_H} = 1 - \frac{400}{1000} = \frac{600}{1000} = 0.6 \text{ or } 60\%$$

$$\eta_{th,IE} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{450}{1000} = \frac{550}{1000} = 0.55 \text{ or } 55\%, \text{ IE and possible.}$$

$$Q_L = 350 \text{ kJ},$$

$$\eta_{th} = 1 - \frac{350}{1000} = \frac{650}{1000} = 0.65 \text{ or } 65\%, \text{ Impossible}$$

19/2/2021



$$T_H = 900^\circ\text{C} = 900 + 273 = 1173 \text{ K}$$

$$T_L = 27^\circ\text{C} = 27 + 273 = 300 \text{ K}$$

$$W \quad Q_H = 800 \text{ kJ/min}$$

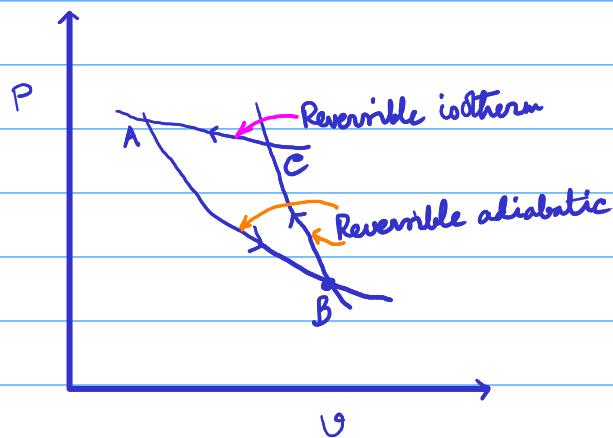
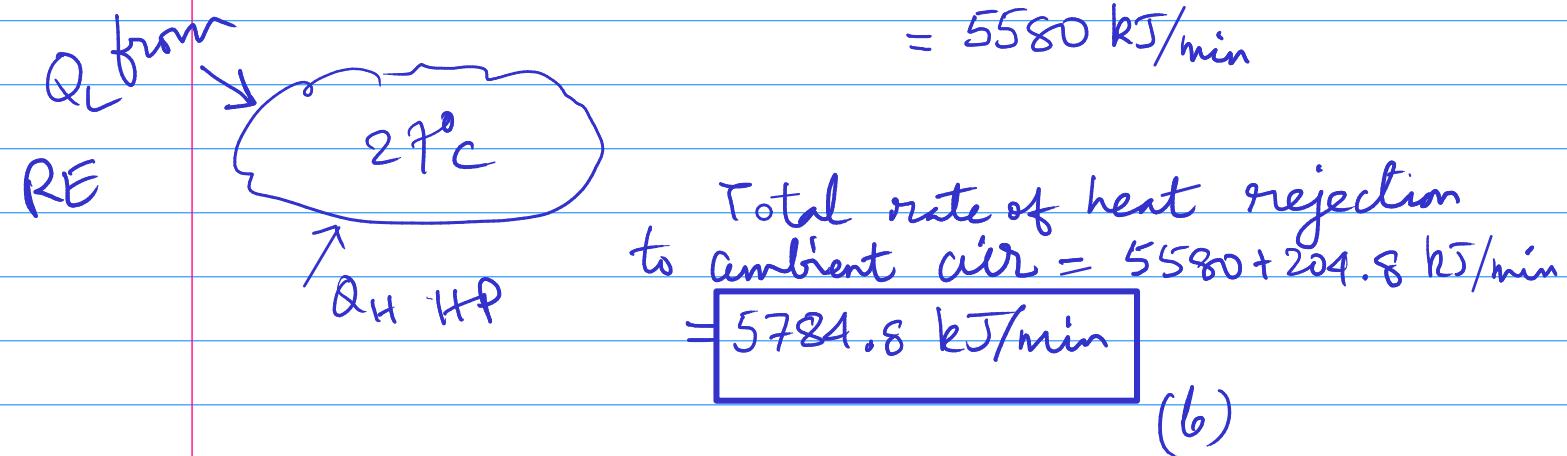
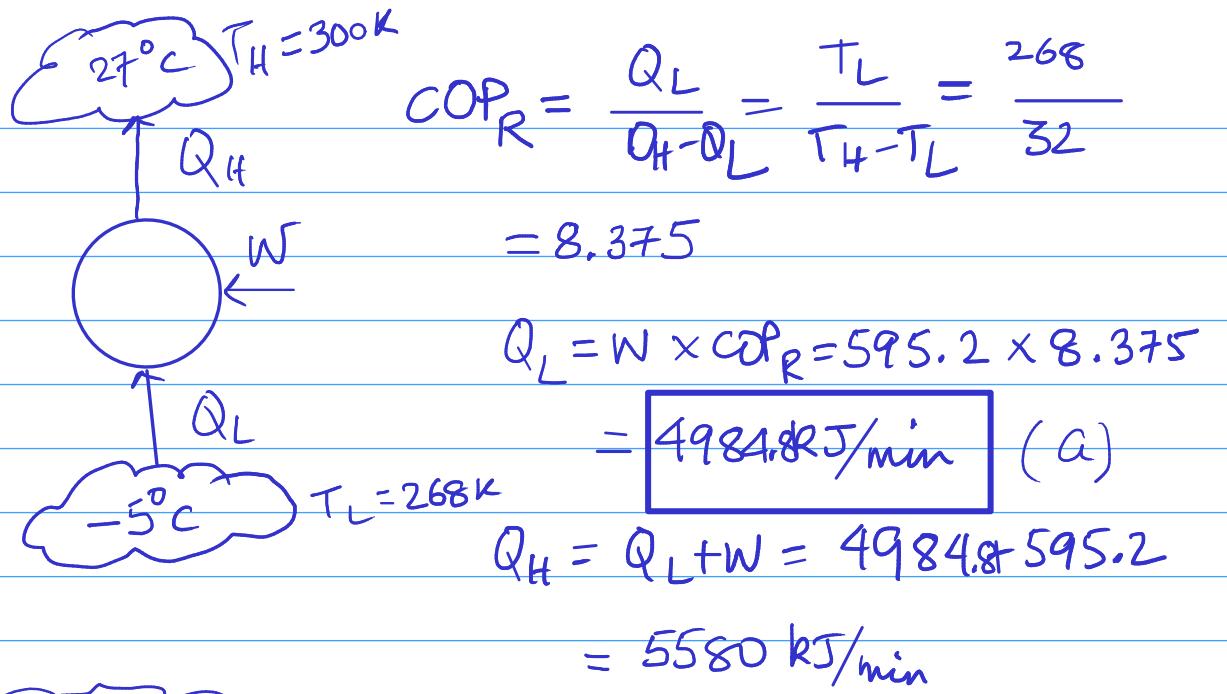
$$\eta_{th,RE} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1173} = 0.744$$

$$W = \eta_{th,RE} \times Q_H = 0.744 \times 800 \\ = 595.2 \text{ kJ/min}$$

$$Q_L = Q_H - W = 800 - 595.2 = 204.8 \text{ kJ/min}$$

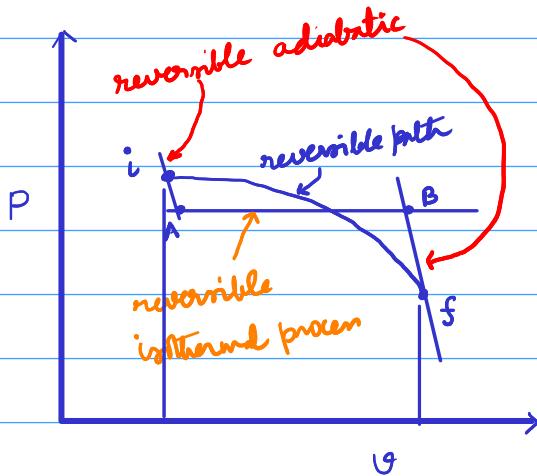
550 kJ/min
 204.8 kJ/min
 $550 - 204.8 = 345.2 \text{ kJ/min}$

r/s



Is this cycle possible?

Violating Kelvin-Planck statement because this cycle is exchanging heat with only one heat reservoir. No two reversible adiabatic can cross each other.

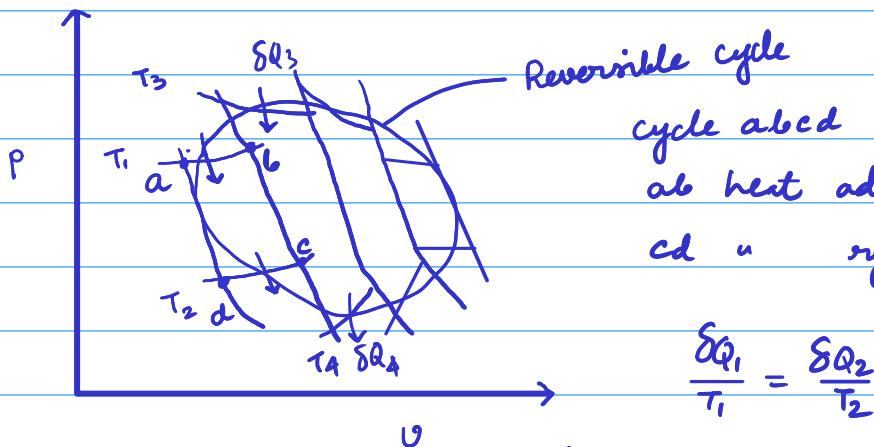


$$Q_{if} - W_{if} = U_f - U_i$$

$$Q_{iABf} - W_{iABf} = U_f - U_i$$

$$W_{if} = W_{iABf}, \text{ then } Q_{if} = Q_{iABf}$$

We can always represent a reversible path by reversible adiabatic followed by reversible isothermal followed by reversible adiabatic such that the heat transferred during the isothermal process is equal to the heat transferred during the original process.



Reversible cycle
cycle abcd reversible
ab heat addition δQ_1 at T_1 ,
cd " rejection δQ_2 at T_2

$$\frac{\delta Q_1}{T_1} = \frac{\delta Q_2}{T_2}$$

If we take the sign convention,

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} = 0$$

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} + \frac{\delta Q_3}{T_3} + \frac{\delta Q_4}{T_4} + \dots = 0$$

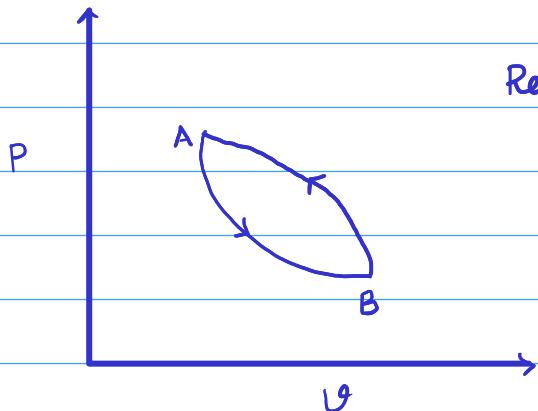
\oint

$$\oint \frac{\delta Q}{T} = 0$$

for reversible cycle.

means

cyclic integral



Reversible cycle

$$\oint \frac{\delta Q}{T} = 0$$

$$\int_{AB}^{} \frac{\delta Q}{T} + \int_{BA}^{} \frac{\delta Q}{T} = 0$$

$$\int_A^B \frac{\delta Q}{T} + \int_B^A \frac{\delta Q}{T} = 0$$

$$\int_A^B \frac{\delta Q}{T} = - \int_B^A \frac{\delta Q}{T}$$

\oint any property = 0

$$\int_A^{AB} \frac{\delta Q}{T} = \int_A^B \frac{\delta Q}{T}$$

$$\boxed{\frac{\delta Q}{T} = dS}$$

reversible process

$$\int_A^B \frac{\delta Q}{T} = \int_A^B dS = [S]_A^B = S_B - S_A$$

Isothermal process: $dS = \frac{\delta Q}{T}$

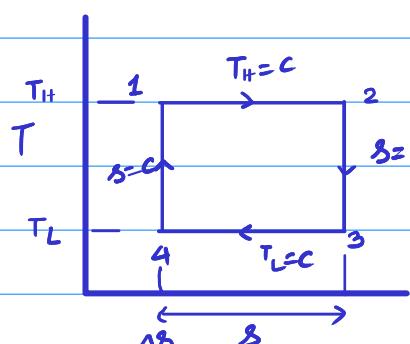
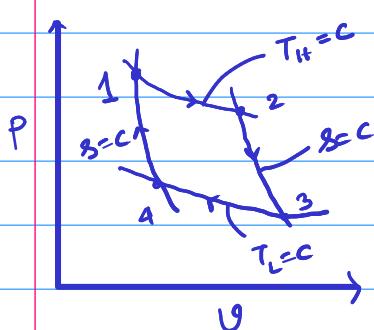
$$S_B - S_A = \frac{1}{T} \int \delta Q = \frac{\Delta Q_B}{T}$$

Reversible adiabatic process: $dS = \frac{\delta Q}{T}$

$$dS = 0 \text{ because } \delta Q = 0$$

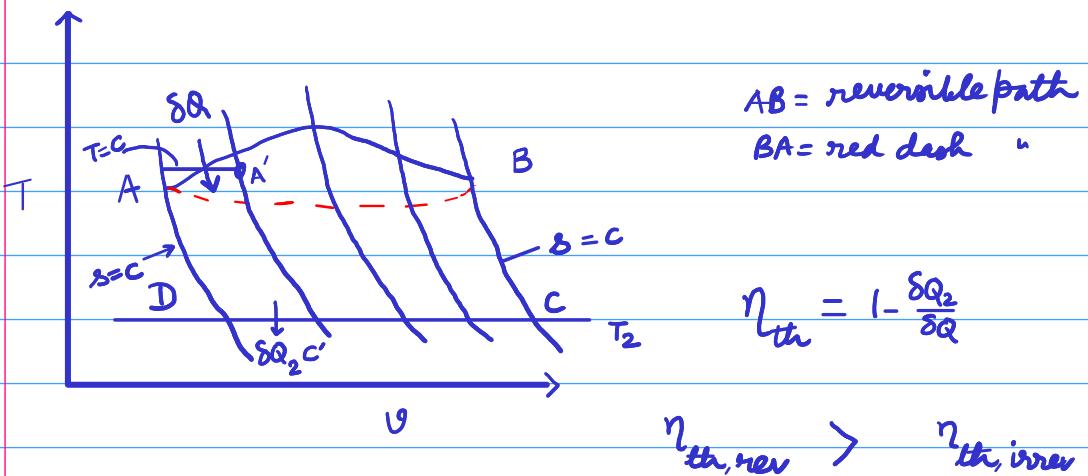
$$dS = 0$$

$S = \text{constant}$



$\Delta S = +ve$ when heat added

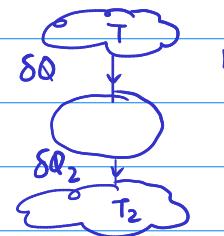
$\Delta S = -ve$ u " rejected



$$\left(1 - \frac{\delta Q_2}{\delta Q}\right)_{\text{rev}} > \left(1 - \frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}}$$

$$\left(\frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}} > \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{rev}}$$

$$\left(\frac{\delta Q}{\delta Q_2}\right)_{\text{irrev}} < \left(\frac{\delta Q}{\delta Q_2}\right)_{\text{rev}}$$



$$\eta_{\text{th}} = 1 - \frac{\delta Q_2}{\delta Q}$$

$$\eta_{\text{th, rev}} = 1 - \frac{\delta Q_L}{\delta Q} = 1 - \frac{T_2}{T}$$

$$\eta_{\text{th, irrever}} = 1 - \frac{\delta Q_L}{\delta Q}$$

$$\left(\frac{\delta Q}{\delta Q_2}\right)_{\text{rev}} = \frac{T}{T_2}$$

$$\left(\frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}} > \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{rev}}$$

$$\left(\frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}} > \frac{T_2}{T}$$

$$\rightarrow \left(\frac{\delta Q}{\delta Q_2}\right)_{\text{irrev}} < \frac{T}{T_2}$$

$$\rightarrow \left(\frac{\delta Q}{T}\right)_{\text{irrev}} < \frac{\delta Q_2}{T_2} \quad \text{reversible process}$$

$$\boxed{\left(\frac{\delta Q}{T}\right)_{\text{irrev}} < ds}$$

$$\frac{\delta Q_2}{T_2} = \frac{\delta Q}{T} \text{ for reversible}$$

$$\oint \frac{\delta Q}{T} \text{ irrev} < \oint ds$$

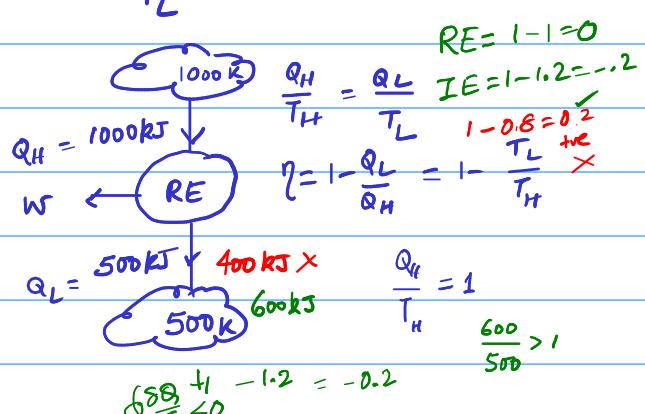
$$\boxed{\oint \frac{\delta Q}{T} \text{ irrev} < 0}$$

$$\boxed{\oint \frac{\delta Q}{T} \text{ rev} = 0}$$

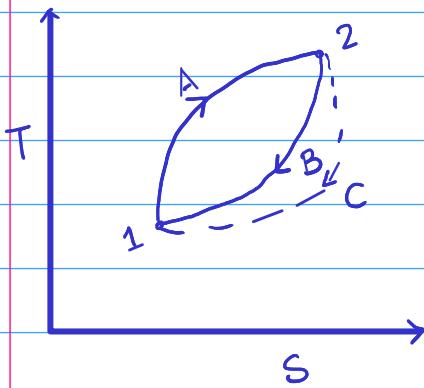
$$\boxed{\oint \frac{\delta Q}{T} > 0}$$

this process violates second law of thermodynamics
and is not possible

$$\boxed{\oint \frac{\delta Q}{T} \leq 0}$$



Entropy change in an irreversible process



Process A and B reversible
Process C is irreversible.
Reversible cycle $|A2B1|$

$$\oint \frac{\delta Q}{T} = 0 \Rightarrow \int_{A'}^2 \frac{\delta Q}{T} + \int_1^{A'} \frac{\delta Q}{T} = 0$$

$$\int_1^2 \frac{\delta Q}{T} = - \int_{B2}^1 \frac{\delta Q}{T}$$

Irreversible cycle $|A2C1|$

$$\oint \frac{\delta Q}{T} < 0 \Rightarrow \int_{A'}^2 \frac{\delta Q}{T} + \int_{C2}^1 \frac{\delta Q}{T} < 0$$

$$-\int_{B2}^1 \frac{\delta Q}{T} + \int_{C2}^1 \frac{\delta Q}{T} < 0$$

$$\int_{B2}^1 \frac{\delta Q}{T} > \int_{C2}^1 \frac{\delta Q}{T}$$

$$\int_{B2}^1 dS > \int_{C2}^1 \frac{\delta Q}{T}$$

$$dS > \frac{\delta Q}{T}$$

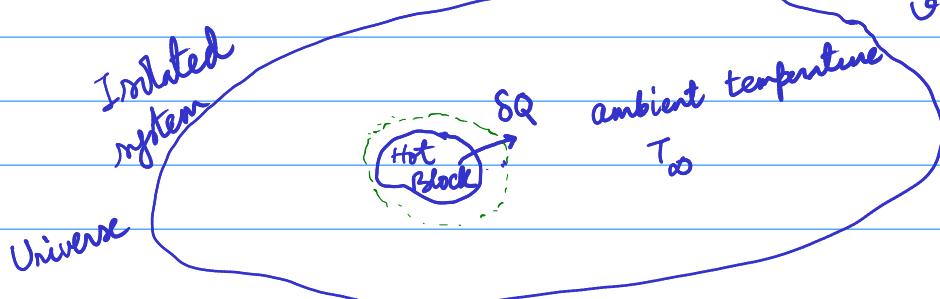
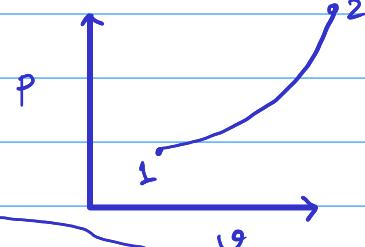
$$\frac{\delta Q}{T} = dS \text{ for reversible}$$

If a process is carried out from state 1 to state 2,

$$(S_2 - S_1)_{\text{rev}} > \int_{1'}^2 \frac{\delta Q}{T}$$

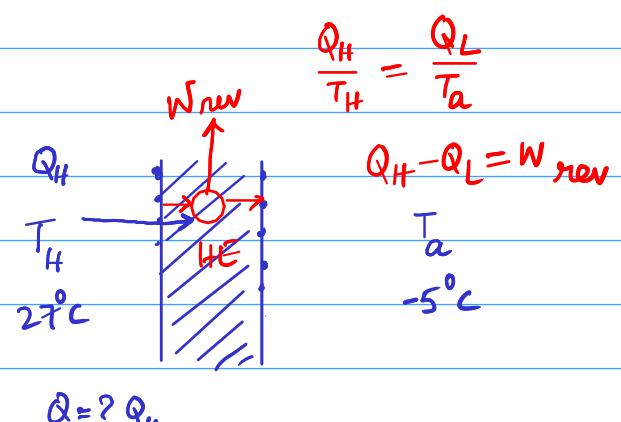
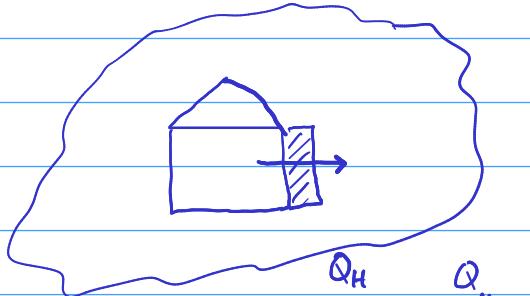
irrever

$$S_2 - S_1 = \int_{\text{irrever}} \frac{\delta Q}{T} + S_{\text{gen}}$$

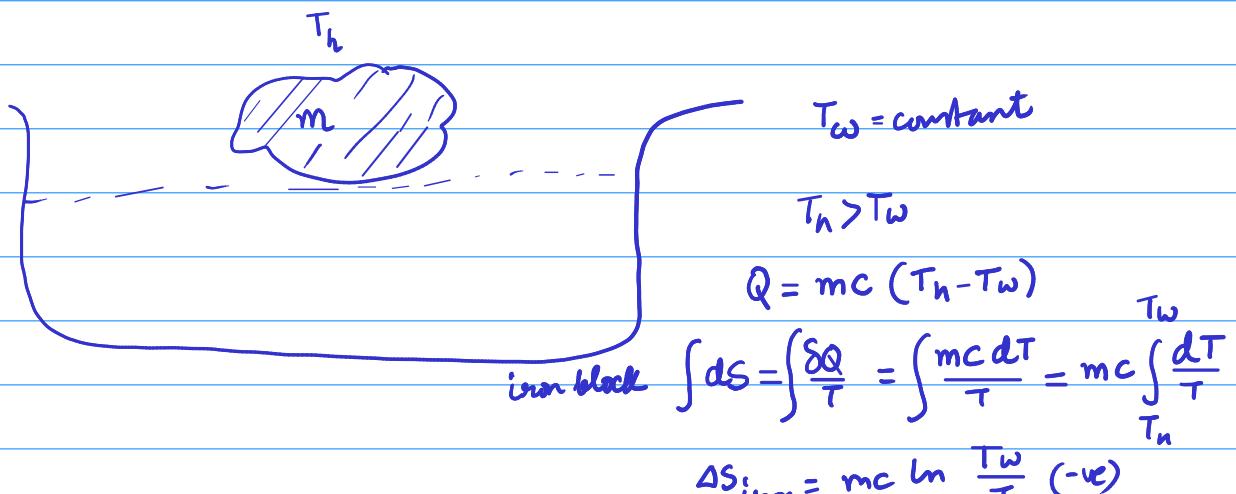


$$(\Delta S)_{\text{univ}} = S_{\text{gen}}$$

Entropy generation principle



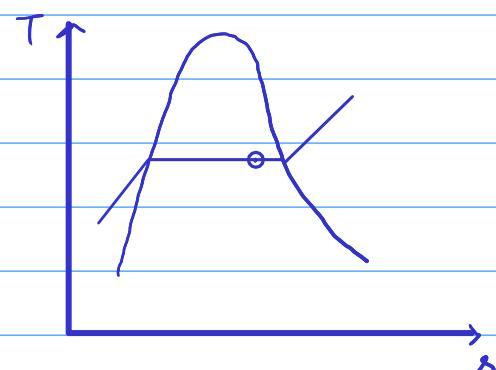
$$\Delta S_{\text{univ}} = \Delta S_{\text{sys}} + \Delta S_{\text{env}} = -\frac{Q_{\text{H}}}{T_{\text{H}}} + \frac{Q_{\text{a}}}{T_{\text{a}}} = Q_{\text{H}} \left(\frac{1}{T_{\text{a}}} - \frac{1}{T_{\text{H}}} \right) = Q_{\text{H}} \left(\frac{1}{268} - \frac{1}{300} \right)$$



$$\Delta S_{\text{env}} = \int \frac{\delta Q}{T} = \frac{1}{T_w} \int \delta Q = \frac{mc(T_h - T_w)}{T_w} \quad (\text{true})$$

$$\Delta S_{\text{univ}} = \Delta S_{\text{sys}} + \Delta S_{\text{env}} = mc \ln \frac{T_w}{T_h} + \frac{mc(T_h - T_w)}{T_w} \quad (\text{true})$$

Entropy change of pure substances



26/2/21

$$dS = \frac{\delta Q}{T}$$

$$\delta Q = T dS$$

$$\delta Q - \delta W = dU$$

$$TdS - PdV = dU$$

$$\delta W = PdV \quad \text{Boundary work}$$

$$TdS = dU + PdV$$

$$TdS = du + Pdv$$

$$\Rightarrow ds = \frac{du}{T} + \frac{P}{T} dv$$

First TdS or Gibbs equation.

$$H = U + PV$$

$$h = u + Pv$$

$$dh = du + Pdv + vdp$$

$$TdS = dh - vdp$$

$$du = c_v dt$$

$$PV = nR_u T$$

$$PV = mRT$$

$$PV = RT$$

$$\int ds = \int v \frac{dT}{T} + \int k \frac{dv}{v} \Rightarrow s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$\Rightarrow ds = \frac{dh}{T} - \frac{v}{T} dp$$

$$s_2 - s_1 = mc_v \ln \frac{T_2}{T_1}$$

Second Tds equation

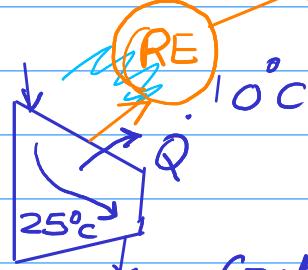
surroundings

7-25

$$\text{Power} = 12 \text{ kW}$$

$$T = 25^\circ\text{C} = 273 + 25 = 298 \text{ K}$$

$$T_a = 10^\circ\text{C} = 273 + 10 = 283 \text{ K}$$



Compressor

$$\delta \dot{Q} - \delta \dot{W} = \dot{m} dh \quad \left| \begin{array}{l} \delta \dot{Q} - \delta \dot{W} = \dot{m} d(h + \frac{v^2}{2} + gz) \\ \dot{Q} = \dot{W} = 12 \text{ kW} \end{array} \right.$$

$$\dot{Q} - \dot{W} = \dot{m} (h + \frac{v^2}{2} + gz) e^{-\dot{m} (h + \frac{v^2}{2} + gz)}.$$

$$\Delta S = \frac{\dot{Q}}{T} = \frac{12}{298} \text{ kW/K} = 0.04027 \text{ kW/K}$$

-ve

$$\Delta S_{\text{univ}} = \Delta S_{\text{sym}} + \Delta S_{\text{surrounding}} = -0.04027 + \frac{12}{283}$$

=

7-34

$$m = 2 \text{ kg}$$

$$P_1 = 100 \text{ kPa}$$

$$\chi = 0.25$$

$$s_1 = 1.3028 + 0.25 \times 6.0562 = 2.81685 \text{ kJ/kg.K}$$

$$v_1 = 0.001043 + 0.25 \times (1.6941 - 0.001043)$$

$$v_1 = v_2 \text{ and } \chi = 1 = 0.4243$$

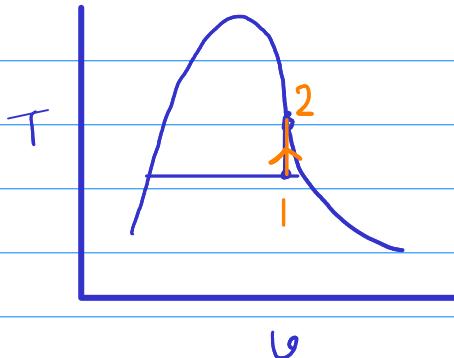
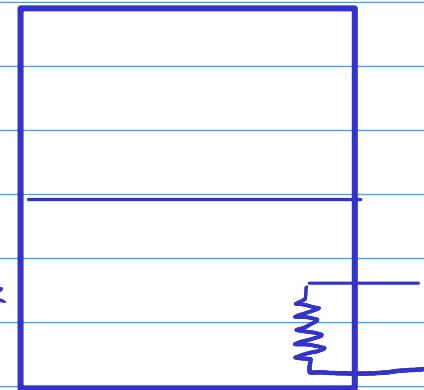
$$s_2 = \checkmark$$

P_2 between 400 and
450

Change in entropy/kgman

$$= (s_2 - s_1)$$

Change in entropy = $m(s_2 - s_1) \text{ kJ/K}$



7-50

state 1

$$P_1 = 6000 \text{ kPa}$$

$$T_1 = 500^\circ\text{C}, T_{sat} = 275.5^\circ\text{C}$$

$$s_1 = 6.8826 \text{ kJ/kg.K}$$

state 2

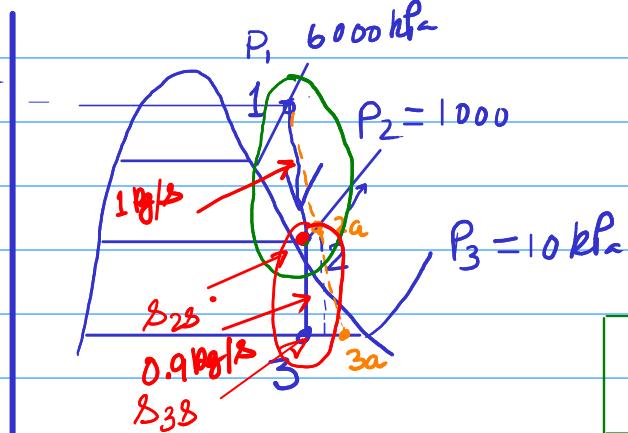
$$P_2 = 1000 \text{ kPa}$$

$$s_2 = s_1, \quad s_g = 6.5850 \text{ kJ/kg.K}$$

$$s_2 > s_g$$

$$h_2 = \checkmark$$

$$\rightarrow T_2 = \checkmark$$



$$s_1 = s_{2s} \quad I$$

$$s_{2s} = s_{3s} \quad II$$

Expansion work in turbine is

isentropic. $s = c$, No heat transfer.

$$\frac{\delta \dot{Q}}{T} = d\dot{S}$$

If $\dot{S} = 0$, $d\dot{S} = 0$

Mass flow rate changes.

$$\dot{m} = 0.9 \text{ kg/sec}$$

$$s_2 = s_3 = s_1 = 6.8826$$

$$s_g = 8.1488$$

$s_3 < s_g$ in the vapour dome

$$s_f = 0.6492$$

Is S is constant or s is constant?

$$\dot{S} = \dot{m}s$$

$$\dot{s}_{3s} - \dot{s}_{2s} = \dot{m}(s_{3s} - s_{2s})$$

$\dot{m} = 0.9 \text{ kg/sec}$ Getting from steam table

$$\dot{s}_{2s} - \dot{s}_1 = \dot{m}_I(s_{2s} - s_1)$$

$$\dot{m}_I = 1 \text{ kg/sec}$$

$$6.8826 = 0.6492 + x \times (8.1488 - 0.6492)$$

$$x = 0.8311$$

$$h_3 = h_f + x \times h_{fg} \quad \checkmark$$

$$\dot{\omega} = 0.9 \times (h_2 - h_3) \quad \text{II}$$

$$\dot{\omega}_I = 1.0 \times (h_1 - h_2)$$

$$\dot{\omega} = \dot{\omega}_I + \dot{\omega}_{II} = 1.0 \times (h_1 - h_2) + 0.9 (h_2 - h_3)$$

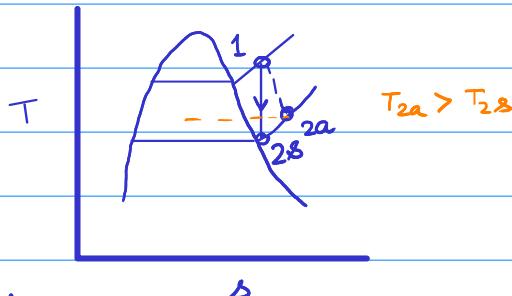
$$\dot{\omega}_I =$$

$$\dot{\omega}_{II} =$$

Isentropic efficiency

$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}}$$

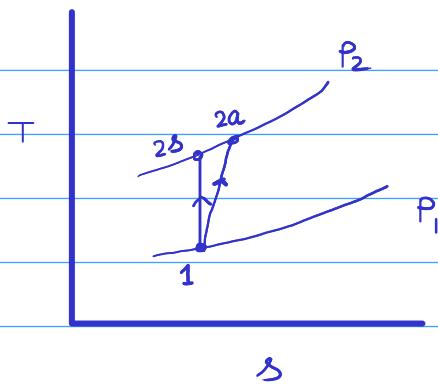
$$= \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \quad \text{neglecting KE and PE}$$



Compressor

$$\eta_c = \frac{\text{Isentropic efficiency}}{\text{Isentropic compressor work}} = \frac{\text{Actual compressor work}}{\text{Isentropic compressor work}}$$

$$= \frac{h_{2s} - h_1}{h_{2a} - h_1}$$



7-57 c_i = specific heat of iron block

$$= 0.45 \text{ kJ/kg·K}$$

$$c_c = 0.39 \text{ kJ/kg·K}$$

$$m_i = \text{mass of iron block} = 50 \text{ kg}$$

$$m_c = \text{mass of copper} = 20 \text{ kg}$$

$$Q_i = \text{heat transfer by iron block} = 50 \times 0.45 \times (80 - 15)$$

=

$$Q_c = \text{heat transfer by copper} = 20 \times 0.39 \times (80 - 15)$$

=

Entropy change of a heated block m_h from temperature

T_h to T_f is

$$dS = m_h \times c_h \times dT/T$$

$$\Delta S = \int_{T_h}^{T_f} m_h c_h dT/T = m_h c_h \ln T_f/T_h$$

$$\Delta S_i = 50 \times 0.05 \times \ln \frac{273+15}{273+80} = -4.58$$

$$\Delta S_c = 20 \times 0.39 \times \ln \frac{273+15}{273+80} = -1.59$$

$$\Delta S_{\text{system}} = \Delta S_i + \Delta S_c =$$

$$\Delta S_{\text{lake}} = \frac{Q}{T} = \frac{Q_i + Q_c}{273+15} = 6.84$$

$$\Delta S_{\text{surrounding}} = \Delta S_{\text{lake}}$$

$$\Delta S_{\text{universe}} = \Delta S_{\text{system}} + \Delta S_{\text{surrounding}} = 0.67 \text{ kJ/K}$$

$$7-67 \quad R_u = 8.314 \text{ kJ/kg-K}; \quad c_v = 0.706 \text{ kJ/kg-K}$$

$$M_{CO_2} = 44 \text{ kJ/kmol}$$

$$R = \frac{8.314}{44} = 0.18895 \text{ kJ/kg-K}$$

$$V = 1.5 \text{ m}^3, \quad P_1 = 100 \text{ kPa},$$

$$m = 2.7 \text{ kg}$$

$$P_2 = 150 \text{ kPa}$$

$$T_1 = 294 \text{ K}, \quad T_2 = 441 \text{ K}$$

$$S_2 - S_1 = 2.7 \times 0.706 \times \ln \frac{441}{294} = 0.773$$

4/3/2021

SFEE

$$\dot{Q} - \dot{W} = \sum m(h + \frac{V^2}{2} + gz)_e - \sum m(h + \frac{V^2}{2} + gz)_i$$

$$\dot{Q} - \dot{W} = \dot{m}_e (h + \frac{V^2}{2} + gz)_e - \dot{m}_i (h + \frac{V^2}{2} + gz)_i$$

Extensive properties

Intensive " "

$$\dot{m}_e = \dot{m}_i = \dot{m}$$

$$q - w = (h + \frac{V^2}{2} + gz)_e - (h + \frac{V^2}{2} + gz)_i$$

$$\delta q - \delta w = dh + d(\frac{V^2}{2}) + d(gz) \quad \text{differential terms.}$$

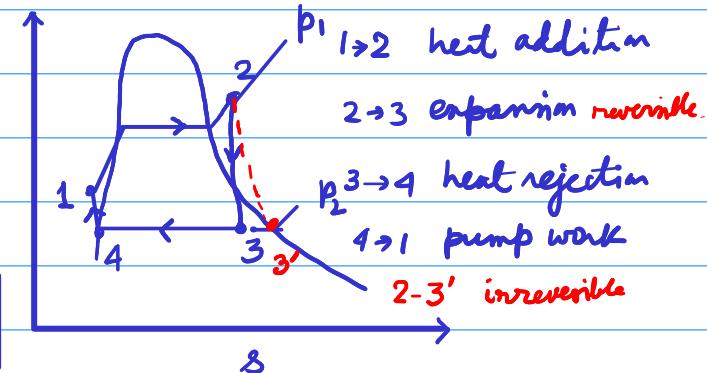
This equation is equally valid whether the proc is reversible or irreversible.

Reversible

$$\delta q = Tds = dh - vdp$$

$$dh - vdp - \delta w = dh + d(\frac{V^2}{2}) + d(gz)$$

$$-\delta w = vdp + d(\frac{V^2}{2}) + d(gz)$$



$$\delta w = 0$$

$$0 = vdp + d(\frac{V^2}{2}) + d(gz)$$

v = constant

$$C = \frac{p_2 - p_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\begin{aligned} \omega_{\text{pump}} &= - \int_4^1 vdp && \text{Pump incompressible} \\ &= -v \int_4^1 dp && \text{Compressor compressible} \\ &= -v(p_1 - p_4) && v \text{ very small} \end{aligned}$$

Bernoulli's equation.

① Reversible frictionless inviscid

② Incompressible

③ Steady

④ Along a streamline

$$\delta w = -vdp - d(\frac{V^2}{2}) - d(gz)$$

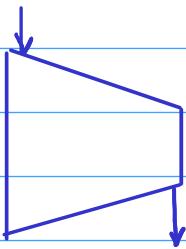
contribution due to $\frac{V^2}{2}$ (K.E.) and gz (P.E.) small compared to other one.

$$\delta U \approx -v dp$$

Reversible work for open system

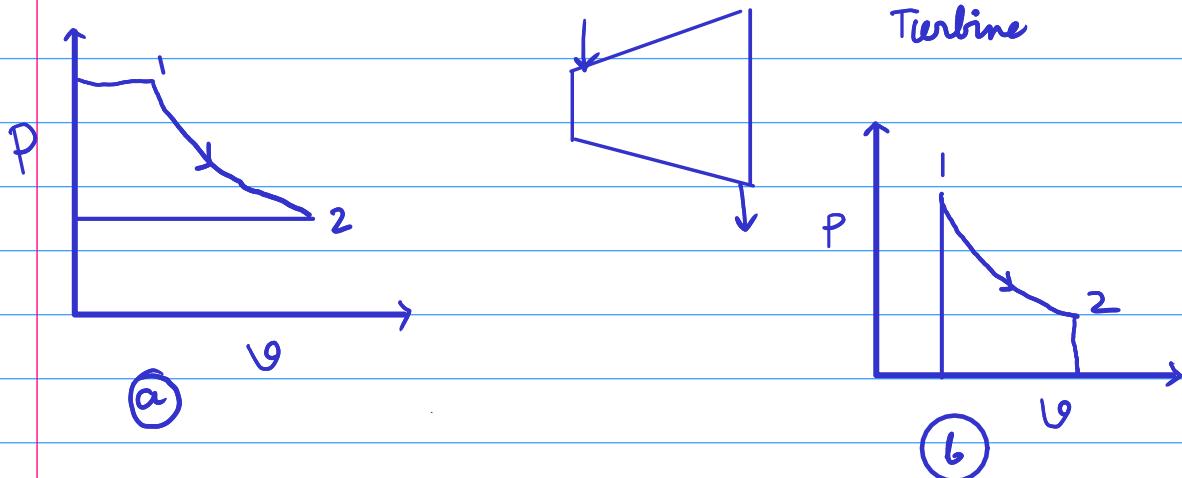
v specific volume

$$w = -\int_1^2 v dp$$



Turbine or compressor ✓

v decreases



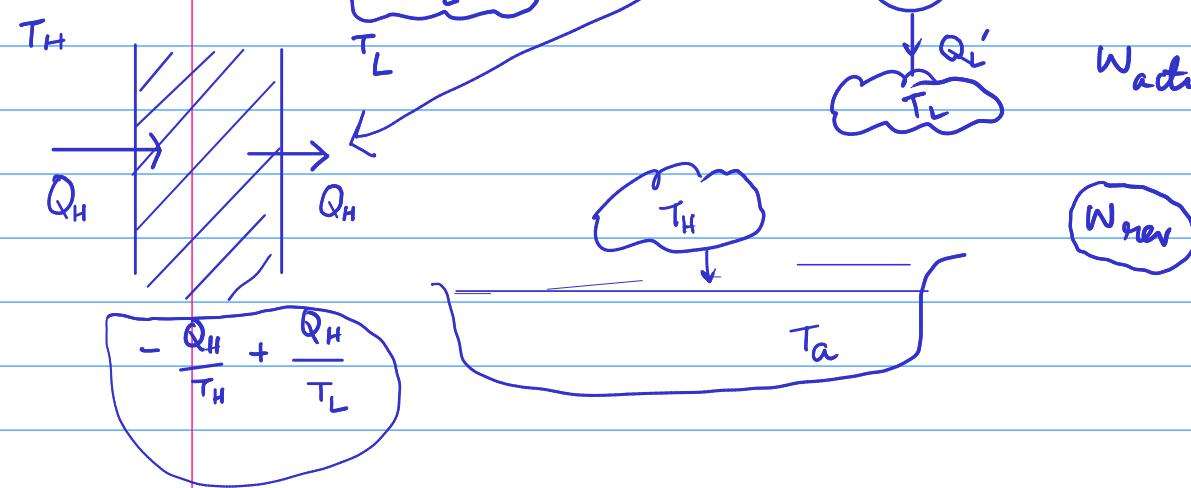
$$W_{rev} = Q_H - Q_L = \eta \times Q_H$$

$$W_{actual} > W_{rev} \times$$

$$= W_{rev}$$

$$< W_{rev} \checkmark$$

$$W_{actual} = 0$$



$$(W_{rev} = \eta_{Carnot} \times Q_H = \left(1 - \frac{T_L}{T_H}\right) Q_H \text{ Lost Work})$$

7-73

$$C_p = 1.005 \text{ kJ/kg-K}$$

$$C_v = 0.718 \text{ kJ/kg-K}$$

$$R = C_p - C_v = 0.287$$

$$\gamma = \frac{C_p}{C_v} =$$

First Tds equation

$$Tds = C_v dT + P dv$$

Second Tds



$$ds = C_v \frac{dT}{T} + \frac{P}{T} dv$$

$$= C_v \frac{dT}{T} + \frac{R}{v} dv$$

$$Tds = dh - vdp$$

$$Tds = CpdT - \frac{v^2}{T} dp$$

$$ds = C_p \frac{dT}{T} - \frac{R}{P} dp$$

$$\checkmark S_2 - S_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= 1.005 \ln \frac{440}{290} - 0.287 \times \ln 6$$

$$= 0.419 - 0.514$$

$$= -0.098 \text{ kJ/kgK}$$

$$\dot{m} = 1.6 \text{ kg/min} = \frac{1.6}{60} \text{ kg/sec}$$

$$S_2 - S_1 = \dot{m} (S_2 - S_1) = \frac{1.6}{60} \times (-0.098) \text{ kJ/kg.K}$$

$$= -0.00261 \text{ kJ/K}$$

Given:

$$T_1 = 17^\circ\text{C} = 290 \text{ K} \quad T_2 = 167^\circ\text{C} = 440 \text{ K}$$

$$P_1 = 100 \text{ kPa}$$

$$P_2 = 600 \text{ kPa}$$

WHICH ONE BETTER
TO USE?

SFEE

$$\dot{Q} - \dot{W} = m(h + \frac{V}{k} + gz)_e - m(h + \frac{V}{k} + gz)_i$$

$$\dot{Q} - (-5) = \frac{1.6}{60} \times c_p \times (T_2 - T_1)$$

$$\dot{Q} = \frac{1.6}{60} \times 1.005 \times (440 - 290) - 5$$

$$= 4.02 - 5$$

$$= -0.98 \text{ kW}$$

- sign indicates that heat is rejected
or lost to the surroundings.

$$\Delta S_{\text{surroundings}} = \frac{0.98}{290} = 0.0034 \frac{\text{kW}}{\text{K}}$$

$$\Delta S_{\text{universe}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$$

$$= -0.00261 + 0.0034$$

$$= 0.0008 \frac{\text{kW}}{\text{K}}$$

7-74

$$TdS = dU + PdV$$

$$dS = \frac{dU}{T} + \frac{P}{T} dV$$

$$PV = nR_u T$$

$$\frac{P}{T} = \frac{nR_u}{V}$$

$$TdS = dU + PdV$$

$$dS = \frac{dU}{T} + \frac{P}{T} dV$$

$$= 0 + \frac{nR_u}{V} dV$$

$$= nR_u \frac{dV}{V}$$

$$S_2 - S_1 = nR_u \ln \frac{V_2}{V_1}$$

$$R_u = 8.314 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$$

$$= 5 \times 8.314 \times \ln 2$$

$$= 28.814 \text{ kJ/K}$$

$$n = 5 \text{ kmol}$$

$$P_1 = 250 \text{ kPa}$$

$$T_1 = 40^\circ\text{C}$$

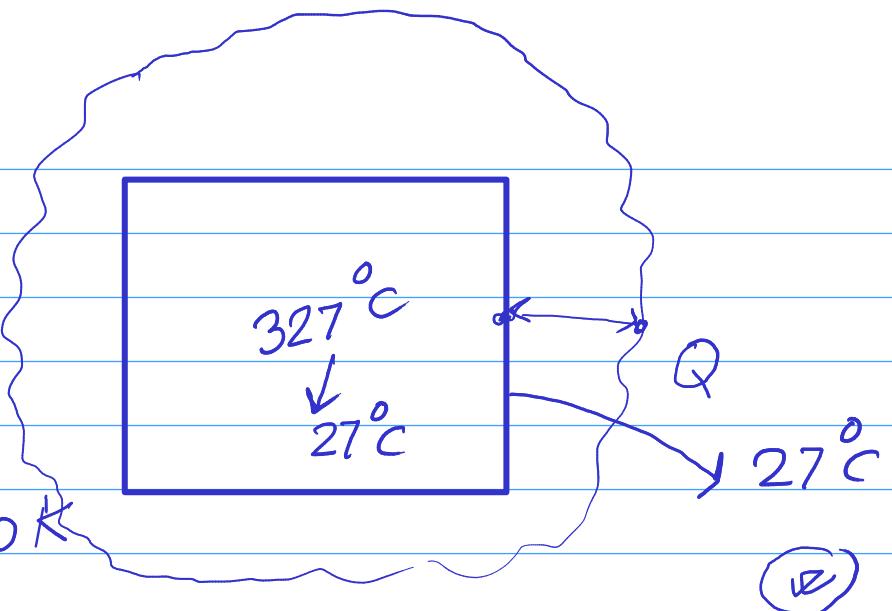
7-86

$$m = 5 \text{ kg}$$

$$P_1 = 100 \text{ kPa}$$

$$T_1 = 327^\circ\text{C} = 600 \text{ K}$$

$$T_2 = 27^\circ\text{C} = 300 \text{ K}$$



(v)

$$\delta_2 - \delta_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$= 0.718 \times \ln \frac{300}{600}$$

$$= -0.4977 \text{ kJ/kg.K}$$

$$S_2 - S_1 = m (\delta_2 - \delta_1) = 5 \times (-0.4977) \text{ kJ/K}$$

$$= -2.488 \text{ kJ/K}$$

$$\text{Heat transfer} = m c_v \Delta T$$

$$= 5 \times 0.718 \times (27 - 327) \text{ kJ}$$

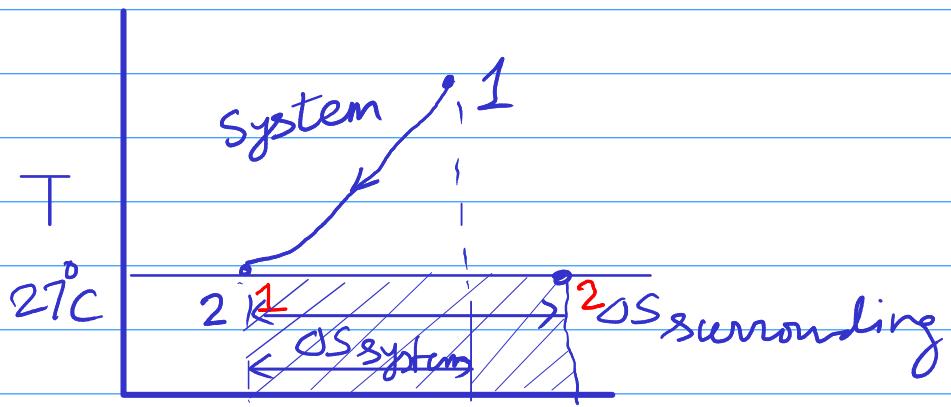
$$= 1077 \text{ kJ}$$

$$\Delta S_{\text{surrounding}} = \frac{Q}{T_a} = \frac{1077}{273+27} = \frac{1077}{300} = 3.59$$

$$\Delta S_{\text{universe}} = \Delta S_{\text{system}} + \Delta S_{\text{surrounding}}$$

$$= -2.488 + 3.59 \frac{\text{RJ}}{\text{K}}$$

$$= 1.102 \text{ RJ/K}$$



δ

$$Q = T_a \times (S_2 - S_1)_{\text{surrounding}}$$

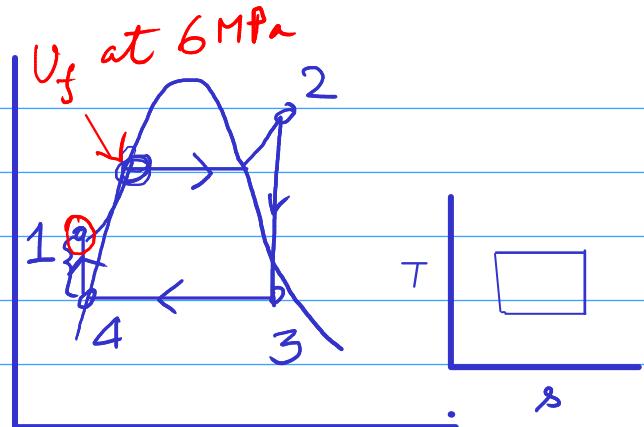
$$\frac{\delta Q}{T} = dS$$

$$\frac{Q}{T_a} = \underline{S_2 - S_1}$$

7-90

$$\omega = - \int_4^1 v dP + \cancel{KE} + \cancel{PE/T}$$

$v \approx \text{constant}$



because incompressible.

$$P_4 = 20 \text{ kPa}$$

60°C

$$P_1 = 6 \text{ MPa}$$

4 → 1 is nearly isothermal

$$\omega = -v(P_1 - P_4)$$

$$\omega = -v \int_4^1 dP$$

$$v = \text{specific volume at } P_4 = -v(P_1 - P_4)$$

$$= V_f \text{ at } P_4 = 20 \text{ kPa}$$

$$= 0.001017 \text{ m}^3/\text{kg}$$

$$\omega = -0.001017 \times (6000 - 20) \text{ kJ/kg}$$

$$= -6.082 \text{ kJ/kg}$$

$$\dot{W} = \dot{m} \omega = 45 \times (-6.082) \text{ kW}$$

$$= -273.67 \text{ kW}$$

10/3/21 Process $4 \rightarrow 1$

SFEE

$$q - w = (h_1 - h_4) + \cancel{KE} + \cancel{PE}$$

$$-(-6.082) = h_1 - h_4$$

$$h_4 = h_f @ P_f = 20 \text{ kPa} = 251.42 \text{ kJ/kg}$$

$$h_1 = h_4 + 6.082$$

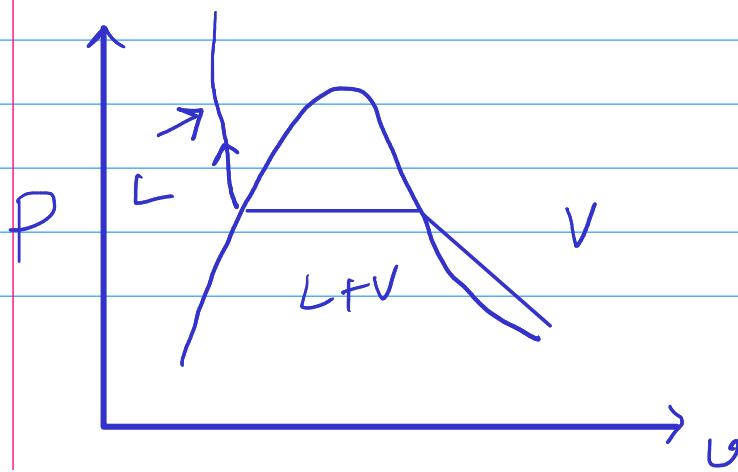
$$= 251.42 + 6.082$$

$$h_f = 257.502 \text{ kJ/kg} \rightarrow \sim 60^\circ\text{C}$$

Condition of h_f $P_i = 6 \text{ MPa}$

$$T_{sat} = 275.59^\circ\text{C}$$

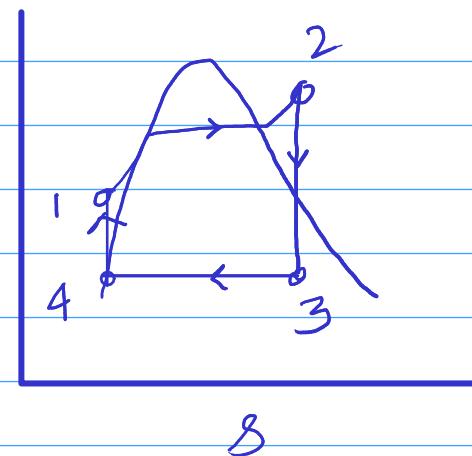
$$h_f = 1213.8 \text{ kJ/kg}$$



7-91

$$W = - \int_{4}^{1} V dP$$

$$= -m\vartheta (P_1 - P_4)$$



$$W = 25 \text{ kW}$$

$$v_f @ 100 \text{ kPa} = 0.001043 \text{ m}^3/\text{kg}$$

$$-25 = 5 \times 0.001 \times (P_1 - 100)$$

$$P_1 = 500 \text{ kPa}$$

7-112

$$T_{28} = ?$$

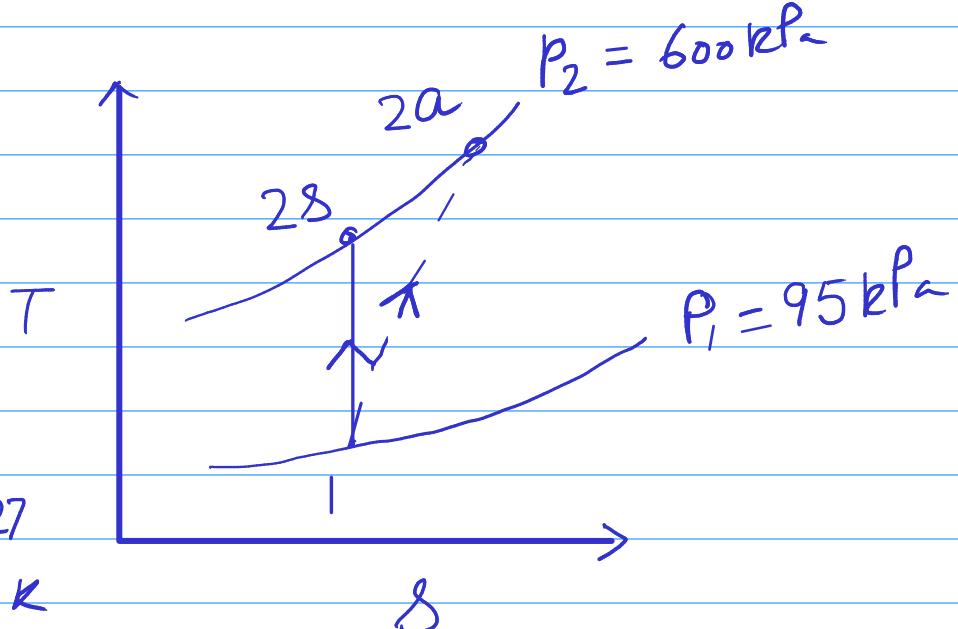
$$\gamma = 1.4$$

$$T_1 = 27^\circ \text{C} = 273 + 27$$

$$= 300 \text{ K}$$

$$P_2 = 600 \text{ kPa}$$

$$P_1 = 95 \text{ kPa}$$



$$P\vartheta^\gamma = C \quad \checkmark$$

$$PV = RT \quad \checkmark$$

$$\frac{T_{28}}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{1}{\gamma}}$$

$$\frac{T_{28}}{T_1} = \frac{P_2 \vartheta_2}{P_1 \vartheta_1}$$

$$T_{28} = 300 \times \left(\frac{600}{95} \right)^{\frac{1}{1.4}} = 1.693 \times 300 = 508 \text{ K}$$

$$\eta_c = \text{Isentropic efficiency of compressor}$$

$$= \frac{\omega_{\text{rev}}}{\omega_{\text{actual}}} = \frac{h_{28} - h_1}{h_{2a} - h_1} = \frac{c_p(T_{28} - T_1)}{c_p(T_{2a} - T_1)}$$

SFEE between 1 and 28

$$\cancel{q_f - w}_{\text{rev}} = (h_{28} - h_1) + \cancel{KE} + \cancel{PE}$$

$$\cancel{q_f - w}_{\text{actual}} = (h_{2a} - h_1) + \cancel{KE} + \cancel{PE}$$

$$T_{2a} = 277^\circ C = 273 + 277 = 550 K$$

$$\eta_c = \frac{T_{28} - T_1}{T_{2a} - T_1} = \frac{508 - 300}{550 - 300} = 0.832 = 83.2\%$$

7-106

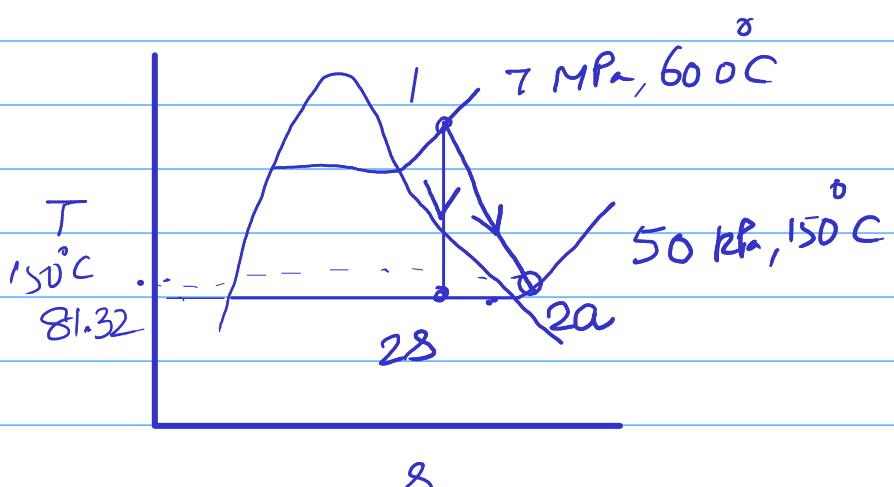
$$T_{2a} > T_{2,\text{sat}}$$

$$h_1 = 3650.6 \text{ kJ/kg}$$

$$\delta_1 = 7.0910 \text{ kJ/kg.K}$$

$$h_{2a} = 2780.2 \text{ kJ/kg}$$

$$\delta_{2a} = 7.9413 \text{ kJ/kg.K}$$



SFEE

$$\dot{Q} - \dot{W} = m(h_{2a} + \frac{v_2^2}{2} + gz_2) - m(h_1 + \frac{v_1^2}{2} + gz_1)$$

$$-6 \times 10^3 = m(h_{2a} - h_1) + m\left(\frac{140^2 - 80^2}{1000 \times 2}\right)$$

$$\dot{m} = 6.84 \text{ kg/s}$$

$$\dot{m} \frac{v^2}{2} = J$$

$$h_{2s} = ?$$

$$\delta_f = \delta_{2s}$$

$$\delta_f = 1.0912$$

$$\delta_g = 7.5931$$

$$\delta_f = 7.0912$$

$$\delta_f = \delta_{2s} < \delta_g \quad \text{wet condition}$$

$$7.0912 = \delta_f + x \times \delta_{fg}$$

$$7.0912 = 1.0912 + x \times (7.5931 - 1.0912)$$

$$x = \frac{7.0912 - 1.0912}{7.5931 - 1.0912} = 0.923$$

$$h_{28} = h_f + 0,923 \times h_{fg} \quad h_f = 340,54 \text{ kJ/kg}$$

$$= 340,54 + 0,923 \times 2304,7 \quad h_{fg} = 2304,7$$

$$= 2467.$$

$$\eta_T = \frac{\omega_{\text{actual}}}{\omega_{\text{reversible}}} = \frac{h_1 - h_{2a} + \left(\frac{v_1^2}{2} - \frac{v_2^2}{2}\right)/1000}{(h_f - h_{28}) + \left(\frac{v_1^2}{2} - \frac{v_2^2}{2}\right)/1000}$$

=

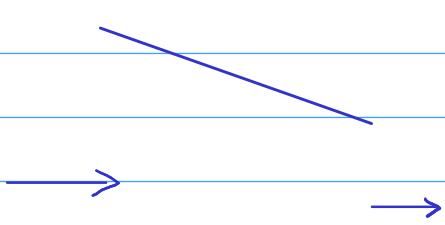
$$Q - \omega = \left(h_2 + \frac{v_2^2}{2}\right) - \left(h_1 + \frac{v_1^2}{2}\right)$$

$$\omega_{\text{act}} = \left(h_1 + \frac{v_1^2}{2} - h_{2a} - \frac{v_2^2}{2}\right)$$

$$\omega_{\text{rev}} = \left(h_1 + \frac{v_1^2}{2} - h_{28} - \frac{v_2^2}{2}\right)$$

11/3/2021

7-117 de Laval nozzle



Pelton wheel

$$P_1 = 260 \text{ kPa},$$

$$T_1 = 747^\circ\text{C} = 747 + 273 \\ = 1020 \text{ K}$$

$$V_1 = 80 \text{ m/s}$$

$$P_2 = 85 \text{ kPa}$$

Air: $c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$, $c_v = 0.718 \text{ kJ/kg}\cdot\text{K}$

$$R = c_p - c_v = 1.005 - 0.718 = 0.287 \text{ kJ/kg}\cdot\text{K}$$

$$\gamma = c_p/c_v = 1.005/0.718 = 1.4$$

SFEE

$$\eta - \psi = (h + \frac{V^2}{2} + gz)_{2S} - (h + \frac{V^2}{2} + gz)_1$$

$$a_V = 0, \omega = 0, PE = 0$$

$$h_{2S} + \frac{V_{2S}^2}{2} = h_1 + \frac{V_1^2}{2}$$

$$\frac{T_{2S}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_{2S} = T_1 \times \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 1020 \times \left(\frac{85}{260}\right)^{\frac{1.4-1}{1.4}} \\ = 740.5 \text{ K}$$

$$\frac{\eta}{N} = \frac{1}{2} V_{2A}^2 / \left(\frac{1}{2} V_{2S}^2 \right)$$

SFEE for 1-2A

$$h_{2A} + \frac{V_{2A}^2}{2} = h_1 + \frac{V_1^2}{2} \Rightarrow \frac{V_{2A}^2}{2} = (h_1 - h_{2A}) + \frac{V_1^2}{2}$$

$$\frac{\eta}{N} = 92\% = 0.92$$

$$0.92 = \frac{(h_1 - h_{2A}) + \frac{V_1^2}{2}}{(h_1 - h_{2S}) + \frac{V_1^2}{2}}$$

Assumption
 $c_p = \text{constant over the temperature range.}$

$$0.92 = \frac{c_p (T_1 - T_{2A}) + \frac{V_1^2}{2}}{c_p (T_1 - T_{2S}) + \frac{V_1^2}{2}}$$

$$0.92 = \frac{1.005 \times (1020 - T_{2A}) + \frac{80^2}{2 \times 1000}}{1.005 \times (1020 - 740.5) + \frac{80^2}{2 \times 1000}}$$

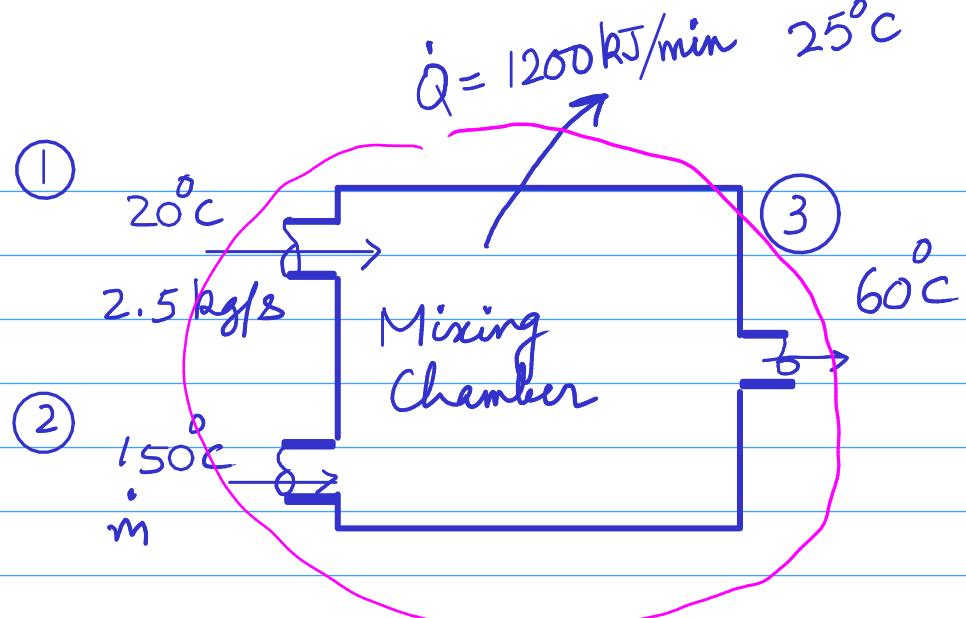
$$0.92 \times [280.9 + 3.2] = 1.005 \times (1020 - T_{2A}) + 3.2$$

$$\frac{261.37 - 3.2}{1.005} = 1020 - T_{2A} \Rightarrow 258.9 = 1020 - T_{2A}$$

$$T_{2A} = 763.1 \text{ K}$$

7-145

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$



SFEE

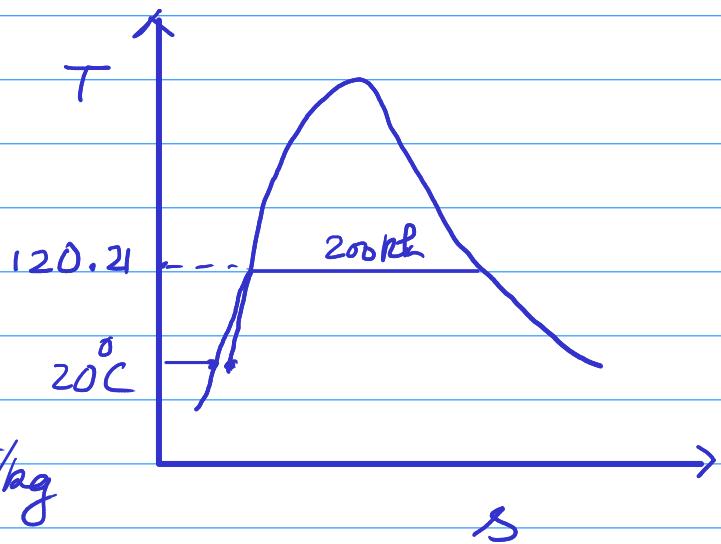
$$\dot{Q} - \dot{W} = \dot{m}_3 h_3 - \dot{m}_1 h_1 - \dot{m}_2 h_2$$

KE and PE neglected

$$-20 = \dot{m}_3 \times 251.18$$

$$-2.5 \times 83.915$$

$$-\dot{m}_2 \times 2769.1$$



$$h_1 = h_f \text{ @ } T_{\text{sat}} = 20^\circ\text{C} = 83.915 \text{ kJ/kg}$$

$$h_2 = 2769.1 \text{ kJ/kg}$$

$$h_3 = h_f \text{ @ } T_{\text{sat}} = 60^\circ\text{C} = 251.18 \text{ kJ/kg}$$

$$-20 - 2.5 \times 251.18 + 2.5 \times 83.915$$

$$= \dot{m}_2 (251.18 - 2769.1)$$

$$\dot{m}_2 = 0.174 \text{ kg/s}$$

17/3/2021

v

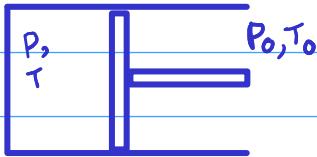
$$KE = \frac{1}{2}mv^2$$

$$PE = mgz$$

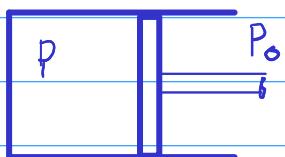
Dead state

$v=0$ (for KE)

$z=0$ (for PE)



P_0, T_0 are dead states for pressure and temperature.
 \downarrow
atmosphere
 $25^\circ C$



$$Q, T \rightarrow T_0, W = \eta_{rev} \times Q$$

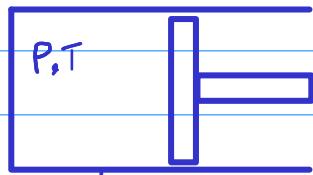
$$= \left(1 - \frac{T_0}{T}\right) \times Q$$

$$W \leq W_{rev}$$

$$W_{rev} = P_0(V_2 - V_1), \quad V_2 = \text{volume after expansion}$$

$V_1 = v$ before v

$$W_u = W - W_{rev} = W - P_0(V_2 - V_1)$$



$$\delta W = PdV$$

$$= (P - P_0)dV + P_0 dV,$$

useful work expended to

overcome the atmospheric pressure.

$\delta W_{HE} \leftarrow \delta Q$

$$\delta Q - \delta W = dU$$

$$-\delta Q - \delta W = dU$$

$$\delta W_{HE} = \left(1 - \frac{T_0}{T}\right)\delta Q = \delta Q - T_0 \frac{\delta Q}{T}$$

$$= \delta Q - (-dS)T_0$$

$$\frac{\delta Q}{T} = -dS$$

$$-\delta W_{total, useful} + T_0 dS - P_0 dV = dU = \delta Q + T_0 dS$$

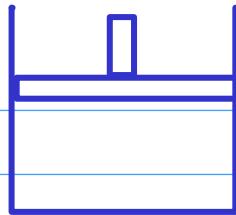
$$\delta Q = \delta W_{HE} - T_0 dS$$

$$\delta W_{total, useful} = -dU - P_0 dV + T_0 dS$$

$$W_{total, useful} = (U - U_0) + P_0(V - V_0) - T_0(S - S_0)$$

$$V_1 = 200 \text{ m}^3, P_1 = 1 \text{ MPa}, T_1 = 300 \text{ K}$$

$$T_0 = 300 \text{ K}, P_0 = 100 \text{ kPa}$$



$$m_1 = \frac{P_1 V_1}{R T_1} = \frac{1000 \times 200}{0.287 \times 300} = 2323 \text{ kg}$$

$$(U_1 - U_0) + P_0(V_1 - V_0) - T_0(S_1 - S_0)$$

$$= P_0 \left[\frac{R T_1}{P_1} - \frac{R T_0}{P_0} \right] - T_0(S_1 - S_0)$$

$$= R T_0 \left[\frac{P_0}{P_1} - 1 \right] - T_0(S_1 - S_0)$$

$$S_1 - S_0 = c_p \ln \left(\frac{T_1}{T_0} \right) - R \ln \frac{P_1}{P_0} = -0.287 \times \ln \frac{1000}{100} =$$

$$= 0.287 \times 300 \left[\frac{100}{1000} - 1 \right] - 0.287 \times \ln \frac{1000}{100}$$

$$\text{Total work} = m \times [(U_1 - U_0) + P_0(V_1 - V_0) - T_0(S_1 - S_0)]$$

$$= 100 \times (R T_0) \times \left[\frac{P_0}{P_1} - 1 \right] - 2323 \times (-0.287) \times \ln 10$$

$$= 281 \text{ MJ}$$

$$\text{Potential to do maximum work} = 281 \text{ MJ}$$

$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + \frac{m V^2}{2} + mgz$$

Exergy or to perform maximum work which occurs at reversible condition only.

$$W_{u,\text{out}}$$

$$W_{\text{rev,out}}$$

$$I = \text{Irreversibility} = W_{\text{rev,out}} - W_{u,\text{out}}$$

$= 0$ reversible

> 0 irreversible

< 0 process is impossible.

State 1 to State 2

$$X_1 = (U_1 - U_0) + P_0(V_1 - V_0) - T_0(S_1 - S_0) + \frac{m V_1^2}{2} + mgz_1$$

$$X_2 = (U_2 - U_0) + P_0(V_2 - V_0) - T_0(S_2 - S_0) + \frac{m V_2^2}{2} + mgz_2$$

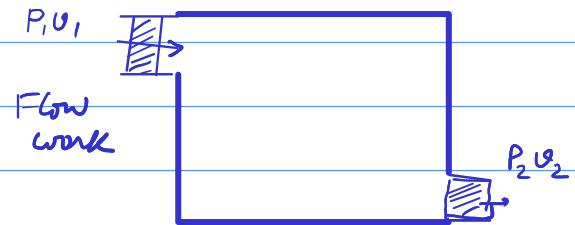
$$x_1 - x_2 = (U_1 - U_2) + P_0(V_1 - V_2) - T_0(S_1 - S_2) + m \frac{V_1^2 - V_2^2}{2} + mg(z_1 - z_2)$$

$$\phi = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + \frac{V^2}{2} + gz$$

$$x = m\phi$$

ψ = flow exergy

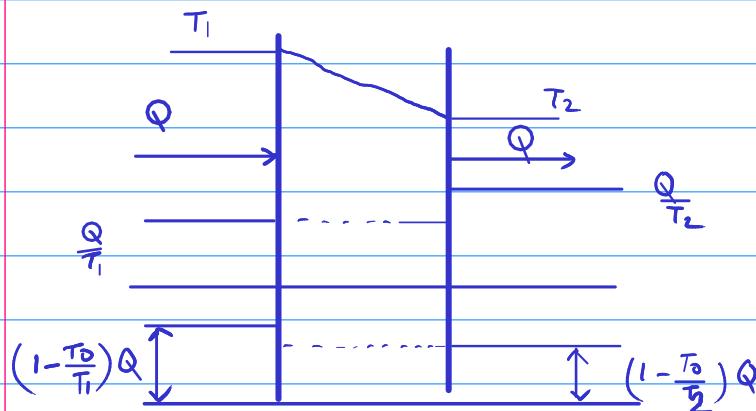
$$\psi = (h - h_0) - T_0(S - S_0) + \frac{V^2}{2} + gz$$



$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) - T_0(S_2 - S_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$\dot{Q} - \dot{W} = (C)_out - (C)_in$$

$$-(\dots + P_2 U_2 - P_1 U_1) = (U_2 + P_2 U_2) - (U_1 + P_1 U_1)$$



Q at temperature T, the reversible work = $Q(1 - \frac{T_0}{T})$

$$x_{heat} = (1 - \frac{T_0}{T})Q$$



$w = \text{Work}$

$$x_{work} = \begin{cases} w - w_{surr} & (\text{for boundary work}) \\ w & (\text{other form of work}) \end{cases}$$

Exergy transfer by man = $m\psi$

$$x_{man} = m\psi$$

18/3/21

Energy balance

$$E_{in} - E_{out} = \Delta E_{system}$$

$$\dot{Q} = E_2 - E_1$$

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system}$$

$$S_{gen} = S_2 - S_1$$

$$T_0 S_{gen} = T_0 (S_2 - S_1)$$

$$-T_0 S_{gen} = E_2 - E_1 - T_0 (S_2 - S_1)$$

$$-T_0 S_{gen} = (E_2 - T_0 S_2) - (E_1 - T_0 S_1)$$

$$\begin{aligned} X_2 - X_1 &= (E_2 - E_1) + P_0 (V_2 - V_1) - T_0 (S_2 - S_1) \\ &= (E_2 - E_1) - T_0 (S_2 - S_1) \end{aligned}$$

$$-T_0 S_{gen} = X_2 - X_1$$

S_{gen} is always positive.

$X_2 - X_1 < 0$
$= 0$
> 0

Inversible

Reversible

Process is not possible

decrease of exergy principle

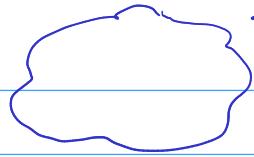
$T_0 S_{gen}$

$$x_{destroyed} = T_0 S_{gen}$$

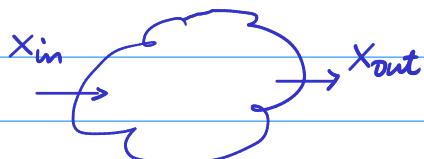
Energy balance: Closed System

$$x_{in} - x_{out} - x_{destroyed} = \Delta x_{system}$$

$$\text{rate form } \dot{x}_{in} - \dot{x}_{out} - \dot{x}_{destroyed} = \frac{dx_{system}}{dt}$$



Isolated System



unit-mass basis

$$(x_{in} - x_{out}) - x_{destroyed} = \Delta x_{system}$$

$$x_{destroyed} = T_0 S_{gen}$$

$$x_{heat} - x_{work} - x_{destroyed} = \Delta x_{system}$$

$$\sum \left(1 - \frac{T_0}{T_K}\right) \dot{Q}_R - [W - P_0(V_2 - V_1)] - T_0 S_{gen} = x_2 - x_1$$

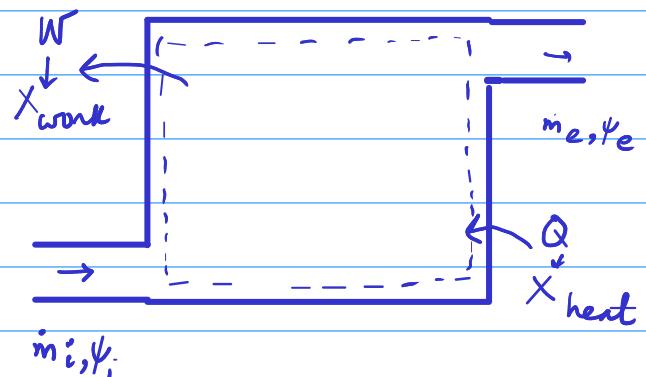
Rate form:

$$\sum \left(1 - \frac{T_0}{T_K}\right) \dot{Q}_R - \left[W - P_0 \frac{dV_{system}}{dt}\right] - T_0 \dot{S}_{gen} = \frac{dx_{system}}{dt}$$

Energy balance: Control Volumes

$$x_{heat} - x_{work} + x_{mass,in} - x_{mass,out}$$

$$-x_{destroyed} = (x_2 - x_1)_{cv}$$



$$\sum \left(1 - \frac{T_0}{T_K}\right) \dot{Q}_R - \left[W - P_0(V_2 - V_1)\right] + \sum_{in} m\psi$$

$$- \sum_{out} m\psi - x_{destroyed} = (x_2 - x_1)_{cv}$$

Rate form

$$\sum \left(1 - \frac{T_0}{T_K}\right) \dot{Q}_R - \left[W - P_0 \frac{dV_{cv}}{dt}\right] + \sum_{in} m\psi - \sum_{out} m\psi - \dot{x}_{destroyed} = \left(\frac{dx}{dt}\right)_{cv}$$

Energy balance for steady flow system

$$\sum \left(1 - \frac{T_0}{T_K}\right) \dot{Q}_R - W + \sum_{in} m\psi - \sum_{out} m\psi - \dot{x}_{destroyed} = 0$$

Single stream

$$\sum \left(1 - \frac{T_0}{T_R}\right) \dot{Q}_R - \dot{W} + m (\psi_1 - \psi_2) - \dot{x}_{\text{destroyed}} = 0 \quad (\text{kJ})$$

Here 1 → inlet

$$\psi_1 - \psi_2 = (h_1 - h_2) - T_0(s_1 - s_2) + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2)$$

2 → outlet

Per unit mass:

$$\sum \left(1 - \frac{T_0}{T_R}\right) q_R - w + (\psi_1 - \psi_2) - \dot{x}_{\text{destroyed}} = 0 \quad (\text{kJ/kg})$$

Reversible work, \dot{W}_{rev}

$$\text{when } \dot{x}_{\text{destroyed}} = 0$$

For single stream → $\dot{W}_{\text{rev}} = m(\psi_1 - \psi_2) + \sum \left(1 - \frac{T_0}{T_R}\right) \dot{Q}_R$

Adiabatic, single stream

$$\dot{W}_{\text{rev}} = m(\psi_1 - \psi_2)$$

8-29

$$P_1 = 100 \text{ kPa}$$

$$P_2 = 600 \text{ kPa}$$

$$P_0 = 100 \text{ kPa}$$

$$T_1 = 25^\circ \text{C}$$

$$T_2 = 150^\circ \text{C}$$

$$T_0 = 25^\circ \text{C}$$

$$V_1 = 2L$$

$$X_1 = (U_1 - U_0) - T_0(S_1 - S_0) + P_0(V_1 - V_0)$$

$$= 0 \text{ kJ}$$

$$X_2 = (U_2 - U_0) - T_0(S_2 - S_0) + P_0(V_2 - V_0)$$

$$m = \frac{P_1 V_1}{R T_1} = \frac{100 \times 2 \times 10^{-3}}{0.287 \times 298} = 0.00234 \text{ kg}$$

$$U_2 - U_0 = c_v (T_2 - T_0) = 0.718 (150 - 25) = 89.75 \text{ kJ/kg}$$

$$\begin{aligned} s_2 - s_0 &= c_p \ln \frac{T_2}{T_0} - R \ln \frac{P_2}{P_0} \\ &= 1.005 \times \ln \frac{423}{298} - 0.287 \times \ln \frac{600}{100} \\ &= -0.1639 \text{ kJ/kg K} \end{aligned}$$

$$\frac{P_2 V_2}{T_2} = \frac{P_0 V_0}{T_0}$$

$$V_2 = 0.000473 \text{ m}^3$$

$$\begin{aligned} x_2 &= m \left[(U_2 - U_0) - T_0 (s_2 - s_0) \right] + P_0 (V_2 - V_0) \\ &= 0.1716 \text{ kJ} \end{aligned}$$

$$W_{rev,in} = 0.1716 \text{ kJ}$$

$$W_{in} = 1.2 \text{ kJ}$$

$$I = W_{in} - W_{rev,in} = (1.2 - 0.1716) \text{ kJ}$$

$$\Delta S_{\text{universe}} = \Delta S_{\text{cv}} + \Delta S_{\text{surrounding}}$$

$$\Delta S_{\text{cv}} = m_3 \delta_3 - m_1 \delta_1 - m_2 \delta_2$$

$$\delta_1 = \delta_f @ T_{\text{sat}} = 20^\circ C = 0.2965 \text{ kJ/kgK}$$

$$\delta_2 = 7.2810 \text{ kJ/kgK}$$

$$\delta_3 = \delta_f @ T_{\text{sat}} = 60^\circ C = 0.8313$$

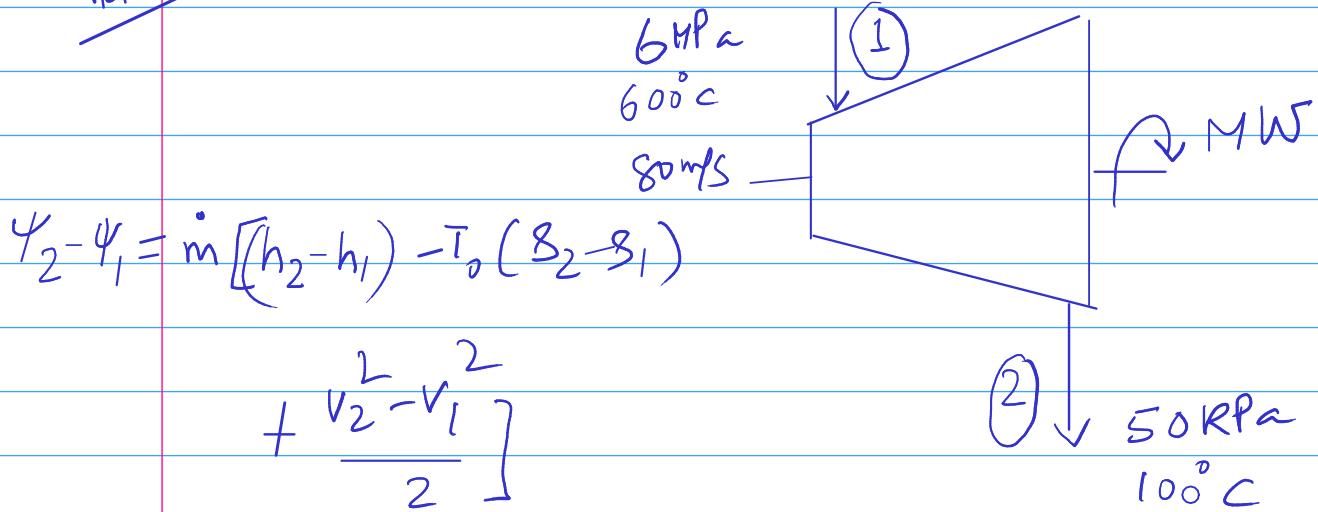
$$\begin{aligned} \Delta S_{\text{cv}} &= (2.5 + 0.174) \times 0.8313 - 2.5 \times 0.2965 \\ &\quad - 0.174 \times 7.2810 \\ &= 0.211 \text{ kJ/K} \end{aligned}$$

$$\Delta S_{\text{surrounding}} = \frac{\dot{Q}}{T_{\text{surrounding}}} = \frac{20}{273+25} = 0.067$$

$$\Delta S_{\text{universe}} = 0.211 + 0.067$$

$$= 0.278 \text{ kJ/K}$$

19/3/2021



$$h_1 = 3658.4 \text{ kJ/kg}, \quad \gamma_1 = 7.1676 \text{ kJ/kg.K}$$

@ 6 MPa, 600°C

$$h_2 = 2682.52 \text{ kJ/kg}, \quad \gamma_2 = 7.6947 \text{ kJ/kg.K}$$

@ 50 kPa, 100°C

$$\gamma_2 > \gamma_1$$

SFEE

$$\dot{Q} - \dot{W} = \dot{m} \left(h_2 + \frac{v_2^2}{2} + g\gamma_2 \right) - \dot{m} \left(h_1 + \frac{v_1^2}{2} + g\gamma_1 \right)$$

$$- 5 \times 10^3 = \dot{m} \left(2682.52 + \frac{140^2}{2000} \right) - \dot{m} \left(3658.4 + \frac{80^2}{2000} \right)$$

$$\dot{m} = 5.158 \text{ kg/s}$$

$$\dot{\Psi}_2 - \dot{\Psi}_1 = \dot{m} \left[(h_2 - h_1) - T_0 (\gamma_2 - \gamma_1) + \frac{v_2^2 - v_1^2}{2} \right]$$

$$= 5.158 \times \left[(2682.52 - 3658.4) - 298 (7.6947 - 7.1676) + \frac{140^2}{2000} - \frac{80^2}{2000} \right]$$

$$= 5809.7 \text{ kW}$$

$$\dot{W}_{\text{rev}} = 5809.7 \text{ kW}$$

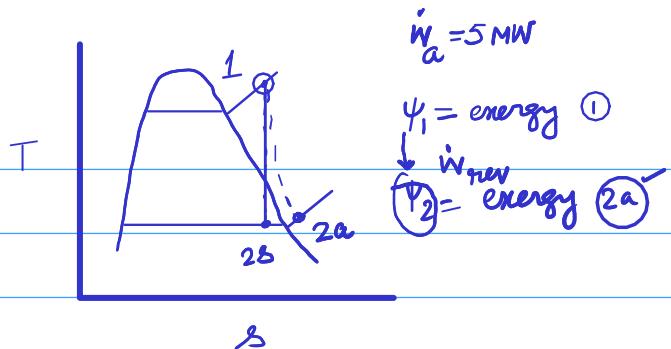
$$\dot{W} = 5000 \text{ kW}$$

$$\text{Irreversibility} = \dot{W}_{\text{rev}} - \dot{W}$$

$$= 5809.7 - 5000 \text{ kW}$$

$$= 809.7 \text{ kW}$$

$$\eta_{II} = \frac{\dot{W}_{\text{actual}}}{\dot{W}_{\text{reversible}}} = \frac{5000}{5809.7} \times 100\% \\ = 86\%$$



Gas Power Cycle

TDC = Top dead center

BDC = Bottom dead center

Stroke volume = stroke length × cross-sectional area of cylinder

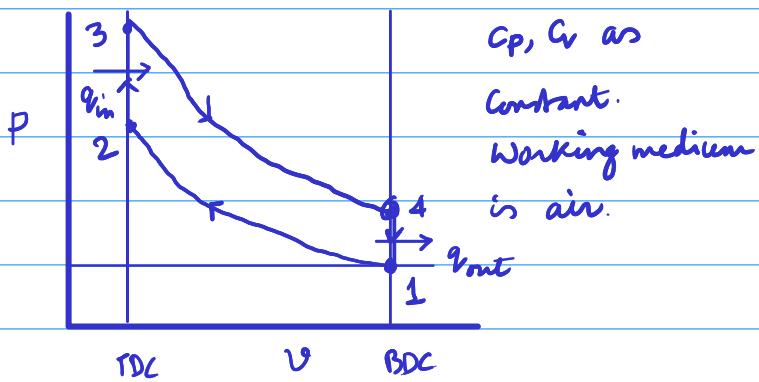
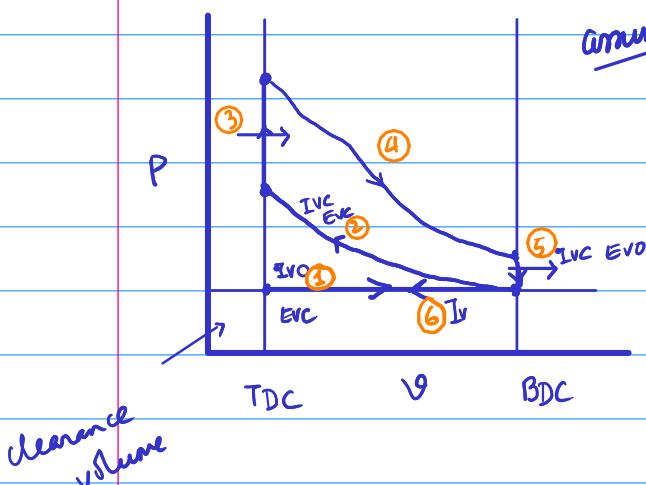
Spark plug in Otto Cycle (Spark ignition, SI engine)

absent in Diesel Cycle (Compression ignition, CI engine)

- ① Suction stroke, ② compression stroke, ③ heat addition process, ④ power stroke,
- ⑤ heat rejection process, ⑥ exhaust stroke.

Air Standard Cycle

Assumption ① and ⑥ they are opposite and equal



Otto Cycle
Indicator diagram.

$$\eta_{th, \text{Otto}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{q_{\text{in}} - q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$$

$$= 1 - \frac{w(T_4 - T_1)}{C_v(T_3 - T_2)}$$

$$r = \text{Compression ratio} = \frac{V_1}{V_2} = \frac{V_4}{V_3}$$

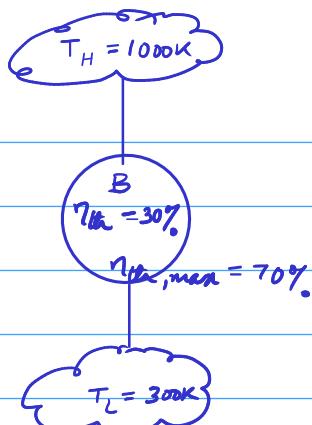
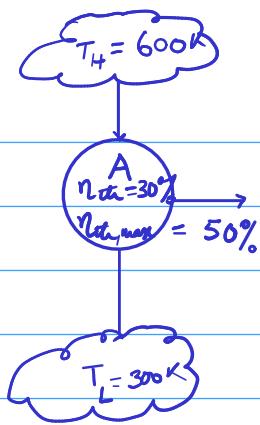
$$= 1 - \frac{1}{r^{k-1}}$$

$$V_1 = V_4, \quad V_2 = V_3$$

$$r = 8 \text{ to } 12 \text{ SI}$$

Knocking
TEL - Tetra ethyl lead

24/3/21



$$= \frac{700}{1000} = 70\%$$

First engine i.e. engine A performs better than engine B

$$\eta_{th} = \frac{W}{Q_{in}}, \quad \eta_{th,max} = \frac{W_{rev}}{Q_{in}}$$

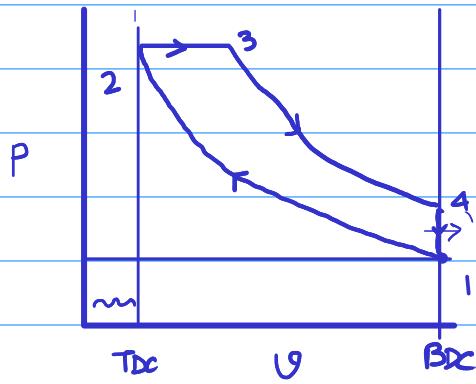
$$\text{engine A} \quad \frac{W}{W_{rev}} = \frac{0.30}{0.50} = 0.6$$

$$\text{engine B} \quad \frac{W}{W_{rev}} = \frac{0.3}{0.7} = 0.4$$

$$\eta_{II} = \frac{W/Q_{in}}{W_{rev}/Q_{in}} = \eta_{th}/\eta_{th,max}$$

Heat engines.

Diesel Cycle



Diesel cycle

Compression ratio is very high
18-22

At the end of process 1-2, temp is very high. Fuel is injected and it ignites on its own.

The fuel needs to be vaporized. Portion moves towards BDC. Simultaneously combustion occurs, vaporization occurs, pressure increases. So combustion is considered as occurring at constant pressure.

1-2-3-4-1 Diesel cycle

H.W

$$q_{in} = c_p(T_3 - T_2), \quad q_{out} = c_v(T_4 - T_1)$$

$$\eta_{th,Diesel} = \frac{W_{net}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)}$$

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

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

$$\eta_{th, Diesel} = 1 - \frac{1}{\gamma-1} \left[\frac{\frac{P_c^{\gamma}}{P_2} - 1}{k(P_c - 1)} \right]$$

If compression ratio is same, $\eta_{th, Diesel} > \eta_{th, Otto}$

In reality, $\eta_{th, Diesel} > \eta_{th, Otto}$

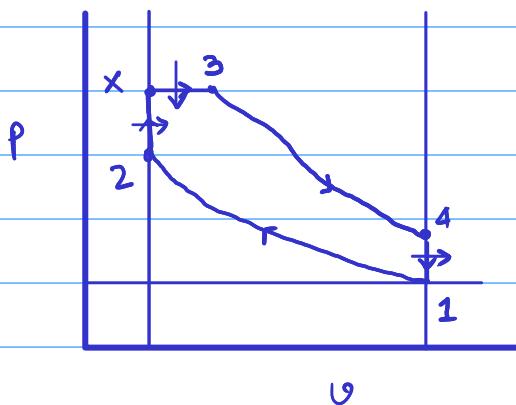
$$\eta_{curr} = 1 - \frac{T_L}{T_H} \Rightarrow T_L \text{ decreasing}$$

T_H increasing

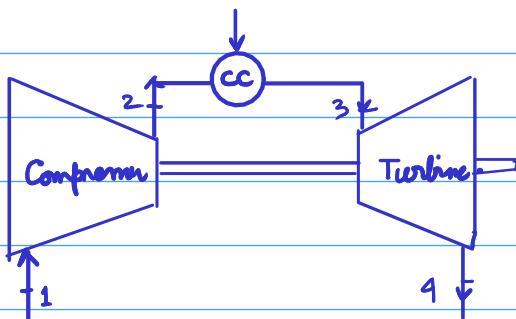
T_2 at the end of compression is high for Diesel eng
compared to SI engine

Average temperature of heat addition is high. So $\eta_{th, Diesel}$ is high.

Dual Cycle

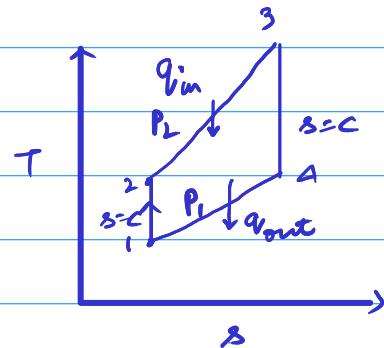
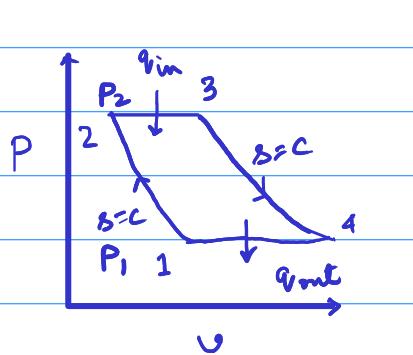


Brayton cycle or Gas Turbine Cycle



$$q_{in} = c_p(T_3 - T_2)$$

$$q_{out} = c_p(T_4 - T_1)$$

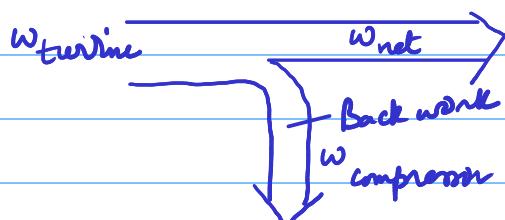


$$\eta_{th, \text{Brayton}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{1}{r^{(k-1)/k}}$$

r_p = Pressure ratio

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



The fraction of the turbine work used to drive the compressor is called the back work ratio.

$$w = - \int v dp$$

25/3/2021

Intermediate pressure = P_x

$P_x = \sqrt{P_1 P_2}$ for minimum compressor work

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

Reheating

400% air supplied

100% 300% excess air

↓ used to combust further in second combustion chamber

Vapour Power Cycle

Carnot cycle

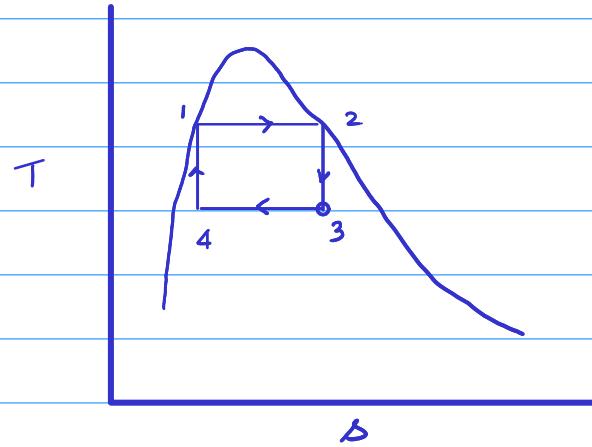
1-2 q_{in}

2-3 w_T

3-4 q_{out}

4-1 w_p

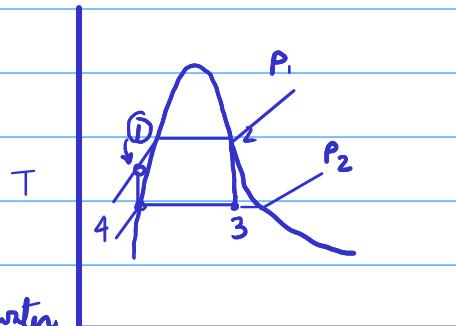
x at 3 is small.



at 4 it is wet steam. Compressing two-phase liquid-gas very difficult.

Modify

Condensation is carried out to saturated liquid line.



Single phase incompressible water

Sp volume of water v_f is very small.

$$w_p = - \int v dP = -v(P_2 - P_1)$$

back work ratio

⇒ Simple ideal Rankine cycle

$$\eta_{th} = \frac{\omega_{net}}{q_{in}}$$

1-2 $q_{in} = h_2 - h_1$

2-3 $\omega_T = (h_2 - h_3)$ $q_v - w = (h + \frac{v^2}{2} + gz)_e - (h + \frac{v^2}{2} + gz)_i$

$2 \rightarrow 3$ $q_v - w = h_3 - h_2$ neglecting KE and PE,
adiabatic turbine $q=0$

3-1 $q_{out} = h_4 - h_3$ $w = (h_2 - h_3)$

$$q_v - w = (h + \frac{v^2}{2} + gz)_e - (h + \frac{v^2}{2} + gz)_i$$

$q_v = h_4 - h_3$ it - ve

4-1 $-w_p = h_1 - h_4$, $w_p = h_4 - h_1$

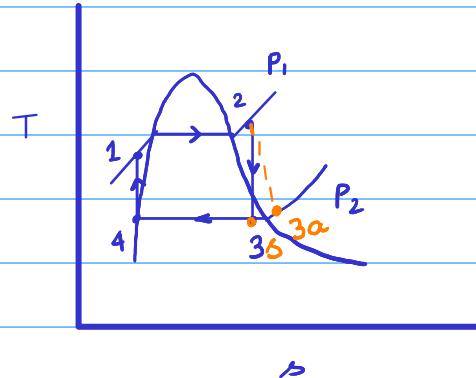
$w_p = -v(P_2 - P_1) = -ve$ value

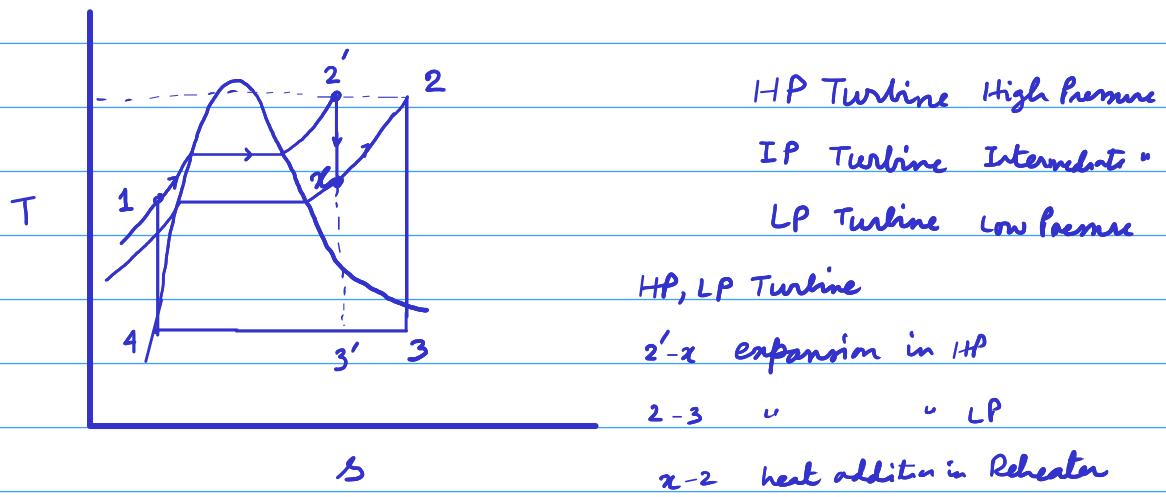
$h_1 = h_4 - w_p$

$h_1 = v$, $h_2 = v$, $h_3 = v$, $h_4 = h_f$ at P_2

$q_{in} = v$
 $w_{net} = \omega_T + w_p$ sign convention

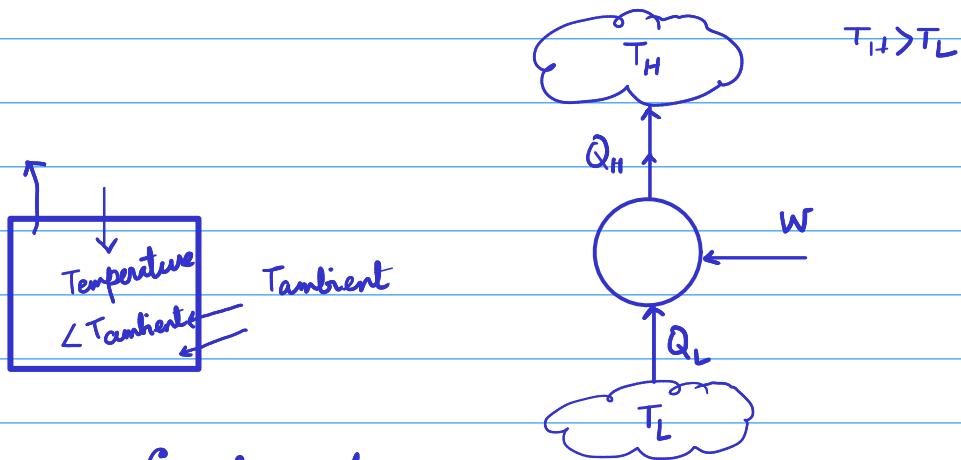
$$\eta_{th} = \frac{\omega_{net}}{q_{in}}$$



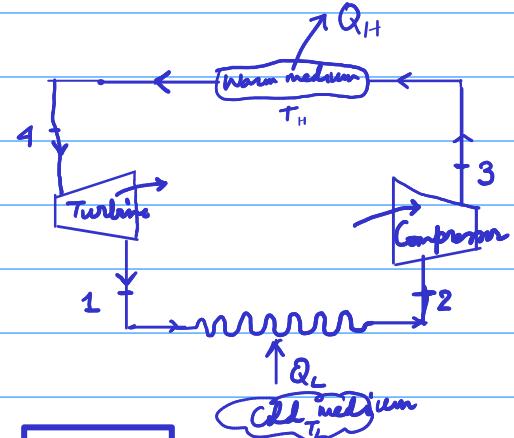
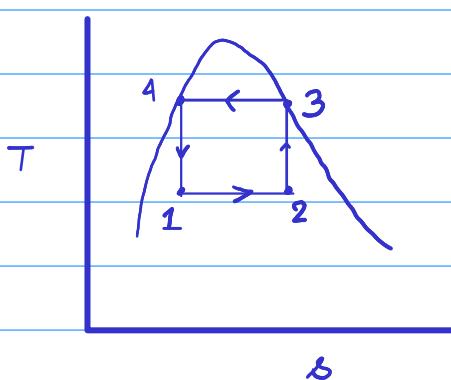


26/3/2021

Refrigeration Cycle



Reverse Carnot cycle

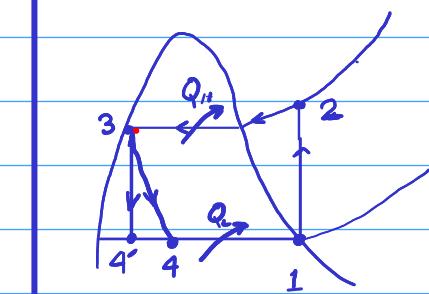


$$COP_{R,\text{Carnot}} = \frac{Q_L}{W_{\text{net}}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1} = \boxed{\frac{1}{\frac{T_H}{T_L} - 1}}$$

$$COP_{HP,\text{Carnot}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}} = \boxed{\frac{1}{1 - \frac{T_L}{T_H}}}$$

1-2-3-4-1

Ideal vapour-compression
refrigeration cycle.

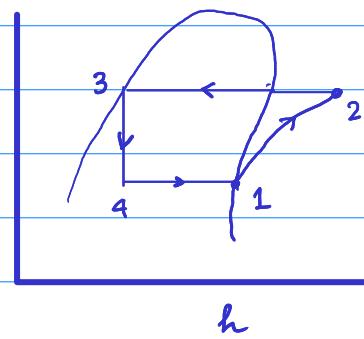


1→2 isentropic compression process
in compressor

2→3 → Heat rejection in condenser at
constant pressure

3→4 → Expansion process in expansion
valve, this is isenthalpic process

4→1 → Heat taken from the refrigerated
space, called evaporator, constant
pressure.



Thermodynamic Property Relations

$$z = z(x, y)$$

$$dz = \frac{\partial z}{\partial x} dx + \frac{\partial z}{\partial y} dy$$

$$= M dx + N dy$$

$$M = \left. \frac{\partial z}{\partial x} \right|_y ; N = \left. \frac{\partial z}{\partial y} \right|_x$$

$$\left. \frac{\partial M}{\partial y} \right|_x = \left. \frac{\partial^2 z}{\partial x \partial y} \right|_z ; \left. \frac{\partial N}{\partial x} \right|_y = \left. \frac{\partial^2 z}{\partial y \partial x} \right|_z$$

$$\left(\frac{\partial x}{\partial z} \right)_y \left(\frac{\partial z}{\partial x} \right)_y = 1 \rightarrow \left(\frac{\partial x}{\partial z} \right)_y = \frac{1}{(\partial z / \partial x)_y} \quad \text{Reciprocity relation}$$

$$\left(\frac{\partial z}{\partial x} \right)_y \left(\frac{\partial x}{\partial y} \right)_z = - \left(\frac{\partial y}{\partial z} \right)_x \rightarrow \left(\frac{\partial x}{\partial z} \right)_y \left(\frac{\partial y}{\partial x} \right)_z \left(\frac{\partial z}{\partial y} \right)_x = -1 \quad \text{cyclic relation}$$

Maxwell Relations

$$du = Tds - Pdv \rightarrow \left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v$$

$$dh = Tds + vdp \rightarrow \left(\frac{\partial T}{\partial p}\right)_s = \left(\frac{\partial v}{\partial s}\right)_p$$

Helmholtz function $a = u - Ts \Rightarrow da = du - Tds - sdT \Rightarrow da = -sdT - Pdv$

Gibbs function $g = h - Ts \Rightarrow dg = dh - Tds - sdT \Rightarrow dg = -sdT + vdp$

$$+\left.\frac{\partial s}{\partial v}\right|_T = +\left.\frac{\partial P}{\partial T}\right|_v$$

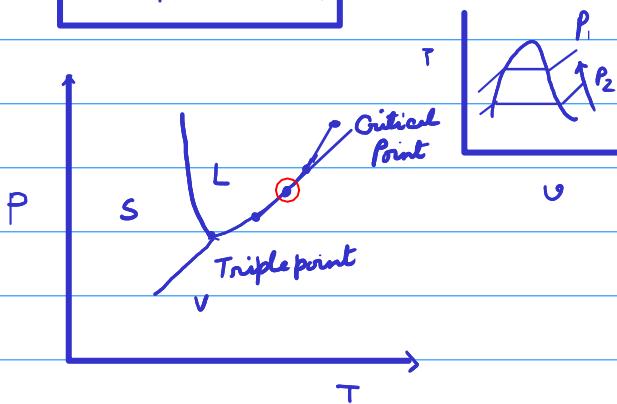
$$\left.\frac{\partial s}{\partial p}\right|_T = -\left.\frac{\partial v}{\partial T}\right|_p$$

Third one

$$\left.\frac{\partial s}{\partial v}\right|_T = \left.\frac{\partial P}{\partial T}\right|_v$$

$$P_{sat} = f(T_{sat})$$

$$\left.\frac{\partial P}{\partial T}\right|_v = \left(\frac{dp}{dT}\right)_{sat}$$



liquid-vapour phase-change

$$\frac{\delta g - \delta f}{v_g - v_f} = \left(\frac{dp}{dT}\right)_{sat}$$

$$\left(\frac{dp}{dT}\right)_{sat} = \frac{\delta_{fg}}{v_{fg}}$$

$$dh = Tds + vdp \quad dh = Tds$$

$$\left(\frac{dp}{dT}\right)_{sat} = \frac{h_{fg}}{T v_{fg}}$$

Clapeyron equation

$v_g \gg v_f$, $v_{fg} \approx v_g$, which follows ideal gas equation

$$v_g = RT/P$$

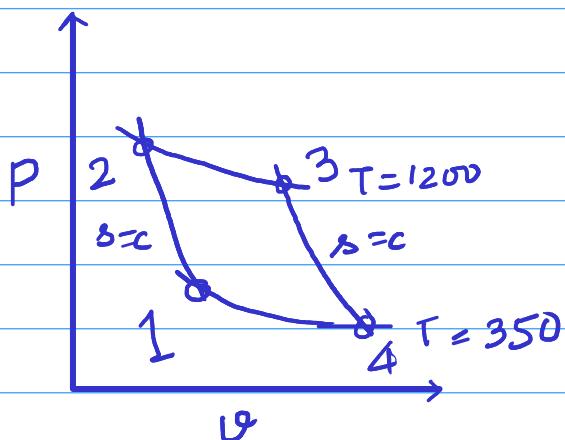
$$\left(\frac{dp}{dT}\right)_{\text{sat}} = \frac{P h_{fg}}{T^2 R}$$

$$\left(\frac{dp}{P}\right)_{\text{sat}} = \frac{h_{fg}}{R} \left(\frac{dT}{T^2}\right)_{\text{sat}}$$

$$\ln\left(\frac{P_2}{P_1}\right)_{\text{sat}} \approx \frac{h_{fg}}{R} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)_{\text{sat}}$$

Clausius-Clapeyron Eqn

Q-23



$$P_1 v_1 = RT_1$$

$$T_1 = 350 \text{ K}$$

$$P_2 v_2 = RT_2$$

$$T_2 = 1200 \text{ K}$$

$$\frac{P_1 v_1}{P_2 v_2} = \frac{T_1}{T_2}$$

$$P_1 = 300 \text{ kPa}$$

$$P_1 v_1^\gamma = P_2 v_2^\gamma$$

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^\gamma$$

$$q_{in} = v$$

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

$$w_{net} = v$$

$$P_2 = v$$

$$m \times w_{net} = 0.5 \text{ kJ}$$

$$m = v$$

3/3/2021

$$du = \left.\frac{\partial u}{\partial T}\right|_v dT + \left.\frac{\partial u}{\partial v}\right|_T dv$$

$$c_v = \left.\frac{\partial u}{\partial T}\right|_v \quad du = c_v dT + \left.\frac{\partial u}{\partial v}\right|_T dv$$

$$ds = \left.\frac{\partial s}{\partial T}\right|_v dT + \left.\frac{\partial s}{\partial v}\right|_T dv$$

$$du = T ds - P dv$$

$$= T \left(\left.\frac{\partial s}{\partial T}\right|_v dT + \left.\frac{\partial s}{\partial v}\right|_T dv \right) - P dv$$

$$= T \frac{\partial s}{\partial T} \Big|_V dT + (T \frac{\partial s}{\partial V} \Big|_T - P) dV$$

$$C_V = T \frac{\partial s}{\partial T} \Big|_V \Rightarrow \frac{\partial s}{\partial T} \Big|_V = \frac{C_V}{T}$$

$$T \frac{\partial s}{\partial V} \Big|_T - P = T \frac{\partial P}{\partial T} \Big|_V - P$$

$$ds = \int_{T_1}^{T_2} C_V dT + (T \frac{\partial P}{\partial T} \Big|_V - P) dV$$

$$u_2 - u_1 = \int_{T_1}^{T_2} \frac{C_V}{T} dT + \int_{V_1}^{V_2} (T \frac{\partial P}{\partial T} \Big|_V - P) dV \quad \checkmark$$

$$dh = \frac{\partial h}{\partial T} \Big|_P dT + \frac{\partial h}{\partial P} \Big|_T dP$$

$$C_P = \frac{\partial h}{\partial T} \Big|_P \quad dh = C_P dT + \frac{\partial h}{\partial P} \Big|_T dP$$

$$ds = \frac{\partial s}{\partial T} \Big|_P dT + \frac{\partial s}{\partial P} \Big|_T dP$$

$$dh = T ds + V dP$$

$$= T \left(\frac{\partial s}{\partial T} \Big|_P dT + \frac{\partial s}{\partial P} \Big|_T dP \right) + V dP$$

$$= T \frac{\partial s}{\partial T} \Big|_P dT + \left(T \frac{\partial s}{\partial P} \Big|_T + V \right) dP$$

$$= T \frac{\partial s}{\partial T} \Big|_P dT + \left(-T \frac{\partial V}{\partial T} \Big|_P + V \right) dP$$

$$T \frac{\partial s}{\partial T} \Big|_P = C_P \Rightarrow \frac{\partial s}{\partial T} \Big|_P = \frac{C_P}{T}$$

$$dh = C_P dT + \left(V - T \frac{\partial V}{\partial T} \Big|_P \right) dP$$

$$h_2 - h_1 = \int_{T_1}^{T_2} C_P dT + \int_{P_1}^{P_2} \left(V - T \frac{\partial V}{\partial T} \Big|_P \right) dP$$

$$h = u + PV$$

$$h_2 - h_1 = (u_2 - u_1) + (P_2 V_2 - P_1 V_1) \quad \checkmark$$

$$ds = \frac{\partial s}{\partial T} \Big|_V dT + \frac{\partial s}{\partial V} \Big|_T dV$$

$$= \frac{C_V}{T} dT + \frac{\partial P}{\partial T} \Big|_V dV \Rightarrow \frac{\partial C_V/T}{\partial V} \Big|_T = \frac{\partial P}{\partial T^2} \Big|_V$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{C_V}{T} dT + \int_{V_1}^{V_2} \frac{\partial P}{\partial T} \Big|_V dV \quad - \quad \frac{\partial C_V}{\partial V} \Big|_T = T \frac{\partial^2 P}{\partial T^2} \Big|_V$$

$$ds = \frac{\partial s}{\partial T} \Big|_P dT + \frac{\partial s}{\partial P} \Big|_T dP$$

$$= \frac{C_p}{T} dT - \frac{\partial v}{\partial T} \Big|_P dP$$

$$\Rightarrow \frac{\partial C_p}{\partial P} \Big|_T = - \frac{\partial^2 v}{\partial T^2} \Big|_P$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{C_p dT}{T} - \int_{P_1}^{P_2} \frac{\partial v}{\partial T} \Big|_P dP$$

$$\frac{\partial C_p}{\partial P} \Big|_T = - T \frac{\partial^2 v}{\partial T^2} \Big|_P$$

$$(C_p - C_v)_T = - T \int_{T_1}^{T_2} \frac{\partial^2 v}{\partial T^2} \Big|_P dT$$

Similar for C_v also.

Either of the above two can be used to find out the change in entropy

$$\frac{C_v}{T} dT + \frac{\partial P}{\partial T} \Big|_V dw = \frac{C_p}{T} dT - \frac{\partial v}{\partial T} \Big|_P dP$$

$$\left(\frac{C_p - C_v}{T} \right)_{\text{ext}} = \frac{\partial v}{\partial T} \Big|_P dP + \frac{\partial P}{\partial T} \Big|_V dw$$

$$dT = \frac{T}{C_p - C_v} \left(\frac{\partial v}{\partial T} \Big|_P dP + \frac{\partial P}{\partial T} \Big|_V dw \right)$$

$$dT = \frac{\partial T}{\partial P} \Big|_V dP + \frac{\partial T}{\partial v} \Big|_P dv$$

$$\left| \frac{T}{C_p - C_v} \frac{\partial v}{\partial T} \right|_P = \frac{\partial T}{\partial P} \Big|_V$$

$$C_p - C_v = T \frac{\partial v}{\partial T} \Big|_P \frac{\partial P}{\partial T} \Big|_V$$

$$\left| \frac{1}{\frac{\partial T}{\partial P}} \right|_V = \frac{\partial P}{\partial T} \Big|_V$$

reciprocity relation

$$\left| \frac{\partial P}{\partial T} \right|_V \left| \frac{\partial T}{\partial v} \right|_P \left| \frac{\partial v}{\partial P} \right|_T = -1 \quad \text{cyclic relation}$$

$$\left| \frac{\partial P}{\partial T} \right|_V = - \left| \frac{\partial v}{\partial T} \right|_P \left| \frac{\partial P}{\partial v} \right|_T$$

$$C_p - C_v = - T \left(\left| \frac{\partial v}{\partial T} \right|_P \right)^2 \left| \frac{\partial P}{\partial v} \right|_T$$

$$\text{volume expansivity } \beta = \frac{1}{V} \left| \frac{\partial v}{\partial T} \right|_P$$

$$\text{isothermal compressibility } \alpha = - \frac{1}{V} \left| \frac{\partial v}{\partial P} \right|_T$$

$$C_p - C_v = \frac{V T \beta^2}{\alpha} \quad \text{Mayer relation}$$

$$C_p - C_v = \text{is always +ve} \quad V = +ve$$

$$T = +ve$$

$$\text{at } T \rightarrow 0 \quad (C_p - C_v) \rightarrow 0 \quad \alpha = +ve$$

β can be positive or negative

$0 \rightarrow 1^\circ C$ negative

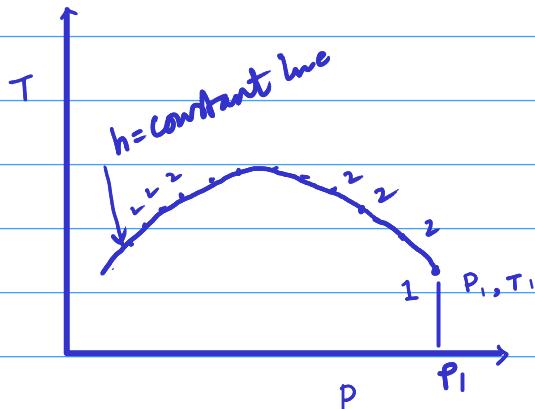
Porous plug

$$\xrightarrow{\quad} P_1, T_1, U_1 \quad \text{[Porous plug]} \quad P_2, U_2, T_2$$

SFEE $h_1 \approx h_2$ isentropic process

P_2 decreases in downstream direction

T_2 may increase or decrease



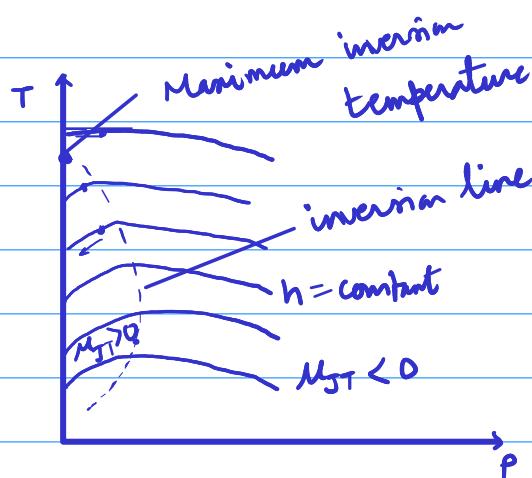
$$M_{JT} = \left(\frac{\partial T}{\partial P} \right)_h$$

$$M_{JT}$$

< 0 temperature increases

= 0 temperature remains constant

> 0 temperature decreases



$$dh = cpdT + \left[v - T \frac{\partial v}{\partial T} |_P \right] dP$$

$h = \text{constant}$

$$0 = cpdT + \left[v - T \frac{\partial v}{\partial T} |_P \right] dP$$

$$M_{JT} = - \left[v - T \frac{\partial v}{\partial T} |_P \right] / cp = \frac{\partial T}{\partial P} |_h$$

What is M_{JT} for an ideal gas?

Gas mixture

molar analysis

gravimetric "

$$\text{mixture mass } m_m = \sum_{i=1}^k m_i \quad N_m = \sum_{i=1}^k N_i$$

m_i = mass of component i

N_i = number of moles of component i

m_m = mass of mixture

N_m = total number of moles of the mixture

$$mf_i = \text{mass fraction} = \frac{m_i}{m_m}$$

$$y_i = \text{mole fraction} = \frac{N_i}{N_m}$$

k

$$\sum_{i=1}^k mf_i = 1 ; \sum_{i=1}^k y_i = 1$$

M_m = apparent (or average) molar mass

$$M_m = \frac{m_m}{N_m} = \frac{\sum m_i}{N_m} = \frac{\sum N_i M_i}{N_m} = \sum \frac{N_i}{N_m} M_i = \boxed{\sum_{i=1}^k y_i M_i} \quad \text{and} \quad R_m = \frac{R_u}{M_m}$$

$$M_m = \frac{m_m}{N_m} = \frac{m_m}{\sum m_i/M_i} = \frac{1}{\sum \frac{m_i}{m_m}/M_i} = \boxed{\frac{1}{\sum_{i=1}^k \frac{mf_i}{M_i}}}$$

$$mf_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \frac{M_i}{M_m}$$

Dalton's law of partial pressure

Amagat's law of partial volume

$$P_i = \text{Partial pressure at } T_m, V_m \rightarrow P_i V_m = N_i R_u T_m$$

$$P_m = \text{Pressure of mixture at } T_m, V_m \rightarrow P_m V_m = N_m R_u T_m$$

$$\boxed{\frac{P_i}{P_m} = \frac{N_i}{N_m} = y_i}$$

$$\boxed{\frac{V_i}{V_m} = y_i}$$

01/04/2021

Properties of Gas mixtures: Ideal gases

$$U_m = \sum_{i=1}^k U_i = \sum_{i=1}^k m_i \bar{u}_i = \sum_{i=1}^k N_i \bar{u}_i \quad \bar{u}_i = \text{internal energy/unit mole}$$

$$H_m = \sum_{i=1}^k H_i = \sum_{i=1}^k m_i h_i = \sum_{i=1}^k N_i \bar{h}_i$$

$$S_m = \sum_{i=1}^k S_i = \sum_{i=1}^k m_i s_i = \sum_{i=1}^k N_i \bar{s}_i$$

$$\Delta U_m = \sum_{i=1}^k \Delta U_i = \sum_{i=1}^k m_i \Delta \bar{u}_i = \sum_{i=1}^k N_i \Delta \bar{u}_i$$

$$\Delta H_m = \sum_{i=1}^k \Delta H_i = \sum_{i=1}^k m_i \Delta h_i = \sum_{i=1}^k N_i \Delta \bar{h}_i$$

$$\Delta S_m = \sum_{i=1}^k \Delta S_i = \sum_{i=1}^k m_i \Delta s_i = \sum_{i=1}^k N_i \Delta \bar{s}_i$$

$$c_{v,m} = \sum_{i=1}^k m_i c_{v,i}$$

$$c_{p,m} = \sum_{i=1}^k m_i c_{p,i}$$

$$\Delta \bar{s}_i = \bar{s}_{i,2} - \bar{s}_{i,1} - R_i \ln \frac{P_{i,2}}{P_{i,1}}$$

$$\bar{\Delta s}_i = \bar{s}_{i,2} - \bar{s}_{i,1} - R_u \ln \frac{P_{i,2}}{P_{i,1}} = \bar{c}_{p,i} \ln \frac{T_{i,2}}{T_{i,1}} - R_u \ln \frac{P_{i,2}}{P_{i,1}}$$

Gas-Vapour mixtures and air conditioning

Mixture of dry air and water vapour.

In atmosphere, we have a mixture of dry air and water vapour in different quantities.

P = Atmospheric pressure, (total pressure)

P_d = Partial pressure of dry air

P_v = " " " water vapour (vapour pressure)

$$P = P_a + P_v$$

For ideal gas, $h_g(T, \text{low } P) \approx h_g(T)$

Enthalpy of water vapour at 0°C 2500.9 kJ/kg .

Average cp value of water vapour in range of -10°C to 50°C can be taken as $1.82 \text{ kJ/kg } ^\circ\text{C}$.

$$h_g(T) \approx 2500.9 + 1.82 T \text{ (kJ/kg)}$$

Atmospheric air, the temperature goes up to 50°C .

Water vapour can be considered to follow ideal gas equation

At low pressure and high temp, this is valid even in less than 0.2%.

$$P_a V = m_a R_a T \quad R_a = \text{Gas constant of dry air} = \frac{R_u}{M_a} \quad M_a \approx 28.97$$

$$P_v V = m_v R_v T \quad R_v = \text{Gas constant of water vapour} = \frac{R_u}{M_v} \quad M_v \approx 18$$

Absolute humidity or specific humidity

$$\omega = \frac{m_v}{m_a} \quad \text{kg of water vapour / kg of dry air}$$

$$= \frac{P_v V}{R_v T} / \frac{P_a V}{R_a T} = \frac{P_v}{P_a} \cdot \frac{R_a}{R_v} = \frac{P_v}{P_a} \cdot \frac{R_u}{M_a} / \frac{R_u}{M_v} = \frac{M_v}{M_a} \cdot \frac{P_v}{P_a}$$

$$\boxed{\omega = 0.622 \frac{P_v}{P - P_v}}$$

Specific humidity ϕ

$$\phi = \frac{m_v}{m_g}$$

If $m_v = m_g$ then $\phi = 1$, saturated air
 $m_v < m_g$ $\Rightarrow \phi < 1$, unsaturated air

$$= \frac{P_v V / R_v T}{P_g V / R_g T} = \frac{P_v}{P_g}$$

$$\boxed{\phi = \frac{P_v}{P_g}}$$

$$P_g = P_{\text{sat}} @ T$$

Saturated pressure at given temperature T

$$\boxed{\omega = 0.622 \frac{\phi P_g}{P - \phi P_g}}$$

$$\boxed{\phi = \frac{\omega P}{(0.622 + \omega) P_g}}$$

$$H = H_a + H_v = m_a h_a + m_v h_v$$

$$h = h_a + \frac{m_v}{m_a} h_v$$

$$h = h_a + w h_v$$

kJ/kg of dry air

$$h_v \approx h_g$$

Usually temperature of air called the dry-bulb temperature (DBT)

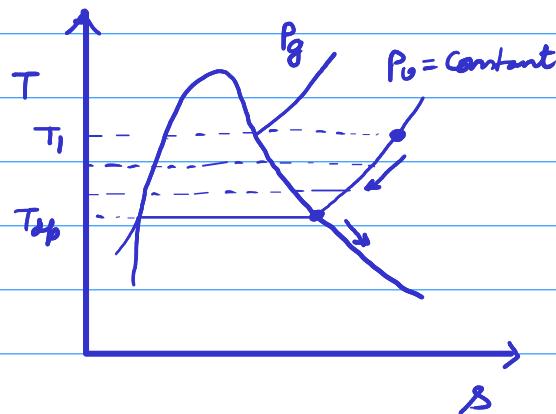
Dew-point temperature

Keeping $P_v = \text{constant}$, if we cool the mixture

Temp corresponding to P_v will be reached

This temperature is called the dew-point temperature

Further cooling, water vapour will start condensing.



Adiabatic saturation and Wet bulb temperature

$$\dot{m}_a = \dot{m}_{a_2} = \dot{m}_a$$

$$\dot{m}_v + \dot{m}_f = \dot{m}_{v_2}$$

$$\dot{m}_a w_1 + \dot{m}_f = \dot{m}_a w_2 \quad ; \quad w = \frac{\dot{m}_w}{\dot{m}_a}$$

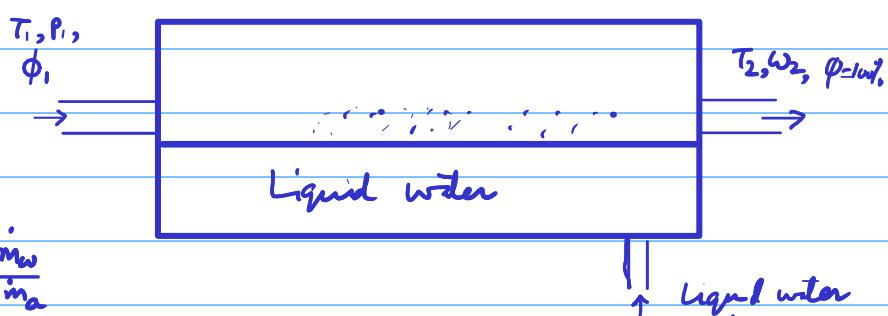
$$\dot{m}_f = \dot{m}_a (w_2 - w_1)$$

SFEE

$$\dot{Q} = \dot{W} = 0, KE = PE = 0$$

$$\dot{m}_a h_1 + \dot{m}_f h_{f_2} = \dot{m}_a h_2$$

$$h_1 + (w_2 - w_1) h_{f_2} = h_2$$

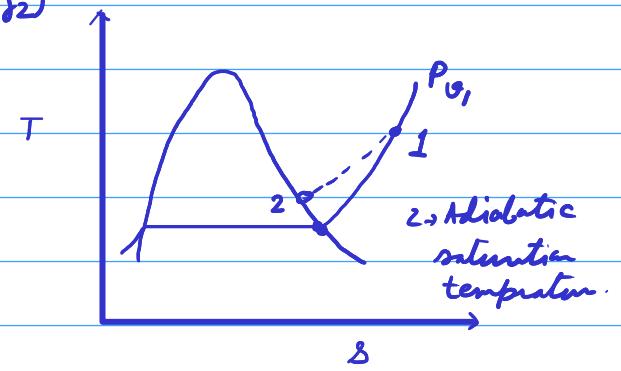


w = absolute or specific humidity

$$(C_p T_1 + w_1 h_{fg1}) + (w_2 - w_1) h_{fg2} = (C_p T_2 + w_2 h_{fg2})$$

$$w_1 = \frac{C_p(T_2 - T_1) + w_2 h_{fg2}}{h_{fg1} - h_{fg2}}$$

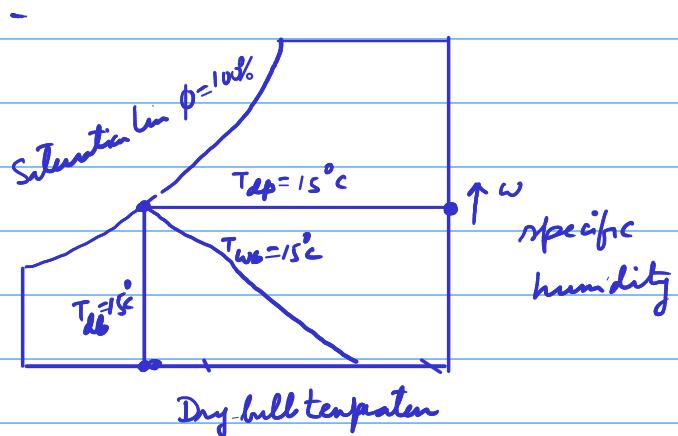
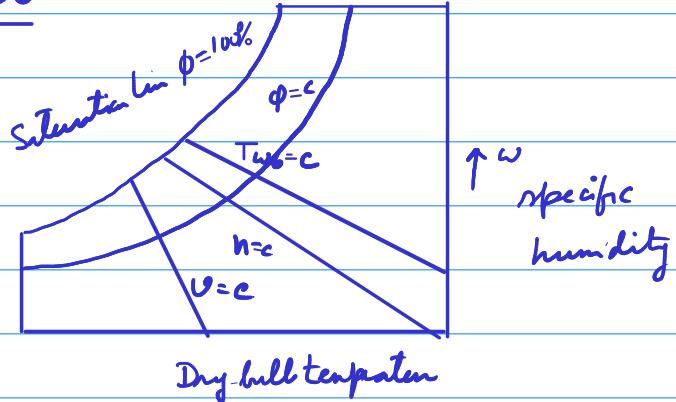
$$w_2 = \frac{0.622 P_{g2}}{P_2 - P_{g2}}$$



Once w_1 is found out, ϕ can be obtained.

This temperature T_2 is called the wet-bulb temperature.

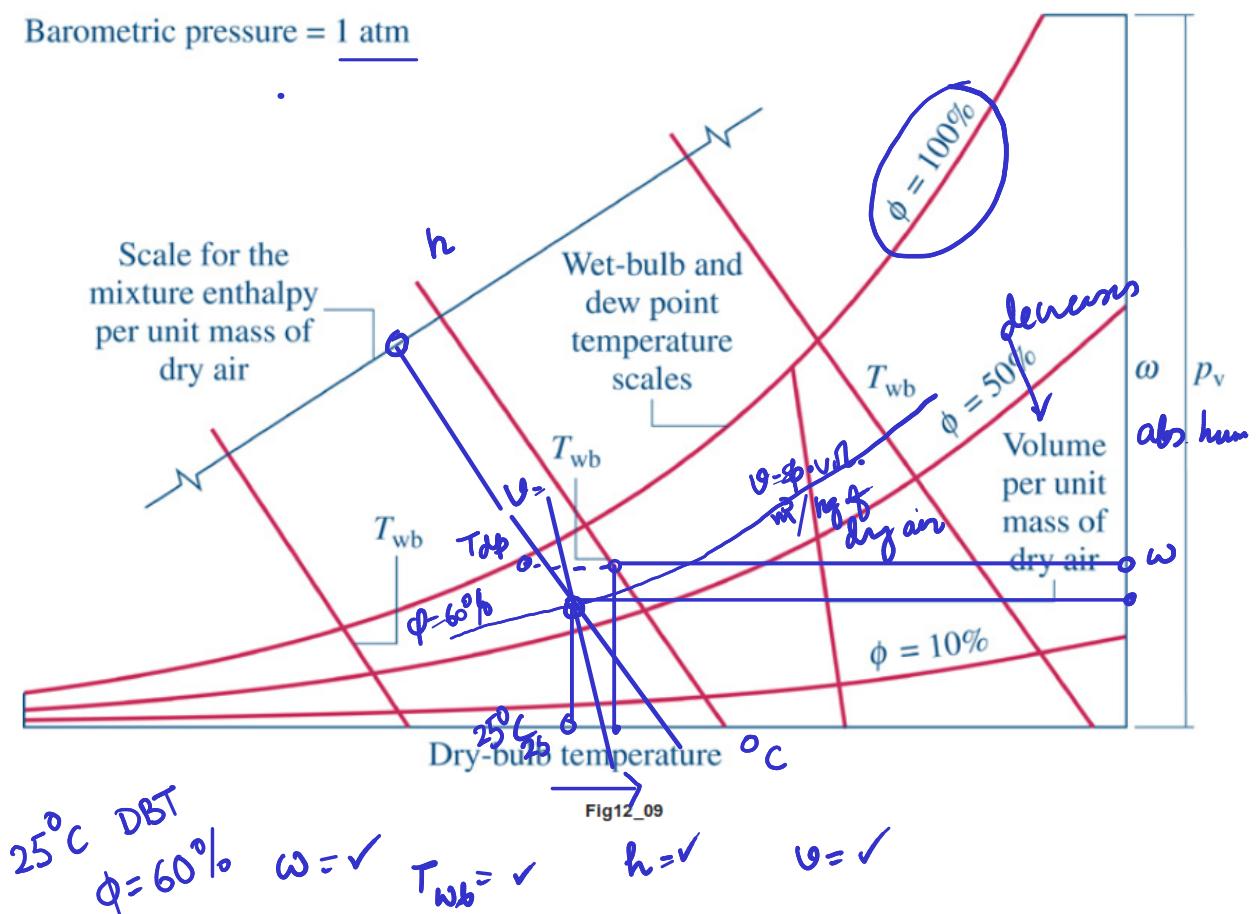
Psychrometric Chart



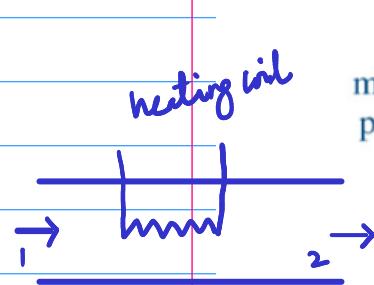
Heating and cooling ($w = \text{constant}$)

Dehumidification and humidification

Barometric pressure = 1 atm



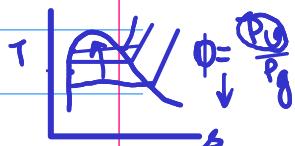
Barometric pressure = 1 atm



Temp will increase

$$\omega = \frac{m_w}{m_a} \text{ constant}$$

$\phi = \text{decrease}$



Scale for the mixture enthalpy per unit mass of dry air

Wet-bulb and dew point temperature scales

$\phi = 100\%$

T_{wb}

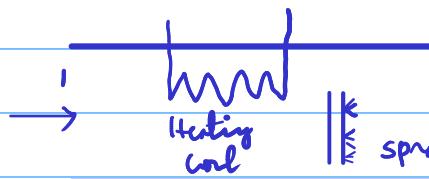
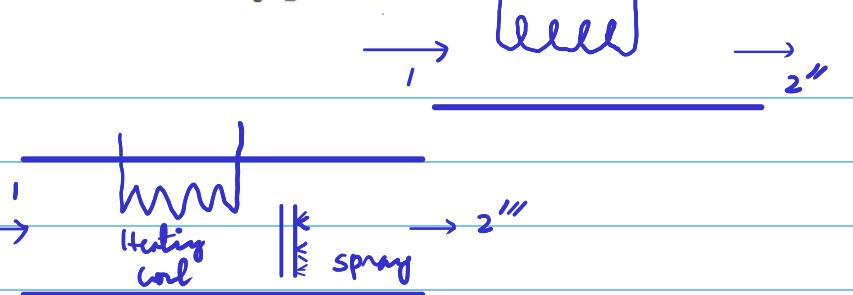
$\phi = 50\%$

Volume per unit mass of dry air

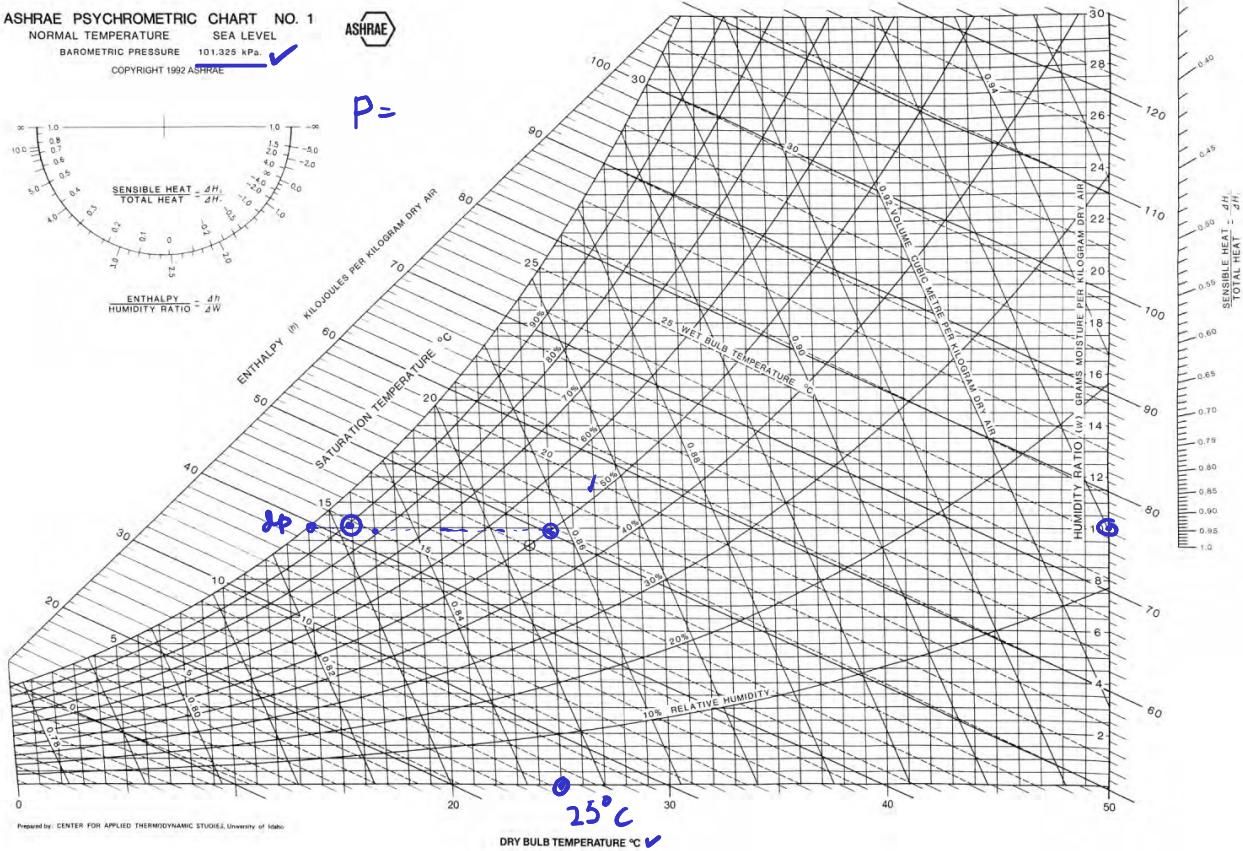
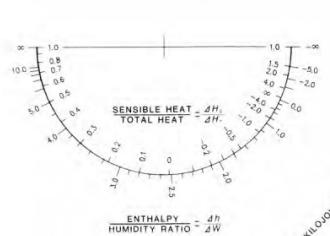
$\phi = 10\%$

Dry-bulb temperature

Fig12_09



ASHRAE PSYCHROMETRIC CHART NO. 1
NORMAL TEMPERATURE SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa. ✓
COPYRIGHT 1992 ASHRAE



$$DBT = 25^\circ\text{C}, \phi = 50\%, w = \frac{10}{100} \frac{\text{kg of moisture}}{\text{kg of dry air}} = 0.1, h_f = 50 \text{ kJ/kg of dry air}$$

$$T_{WB} = 17.5^\circ\text{C} \quad T_{dp}$$

wall cooling

$$h_1 = 50 \text{ kJ/kg of dry air}$$

(1)

(2)

$$Q = 100 \text{ kW/sec}$$

$$h_2 = ?$$

$$\dot{Q} - \dot{W} = \dot{m}_a (h + \frac{V^2}{2} + gz)_2 - \dot{m}_a (h + \frac{V^2}{2} + gz)_1$$

$$\dot{W} = 0, \text{ KE and PE} = 0$$

$$\dot{Q} = \dot{m}_a (h_2 - h_1) \Rightarrow -100 = \dot{m}_a (h_2 - h_1)$$

$$\dot{m}_a = 15 \text{ kg/sec} \quad h_2 = h_1 - \frac{100}{15} = 50 - 6.7 = 43.3 \text{ kJ/kg}$$

$$\phi = \checkmark$$

$$v_1 = 0.86 \text{ m}^3/\text{kg of dry air}$$

$$\text{Area of duct} = 0.1 \text{ m}^2$$

8/4/2021

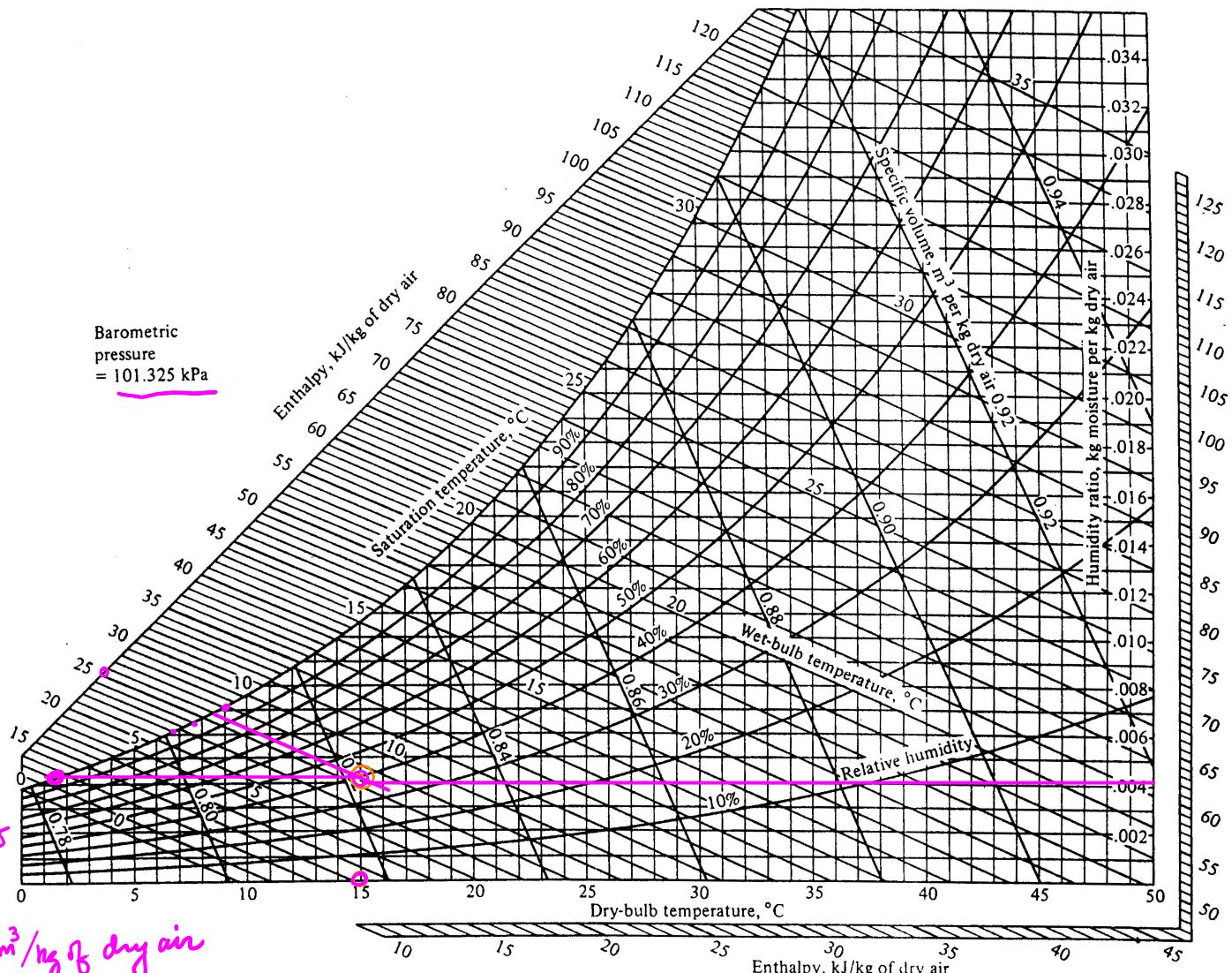
Volume = 100 m^3 of atmospheric air

Atmospheric pressure = 101325 kPa , Temperature = 15°C
dry bulb temperature

ϕ = relative humidity = 40%

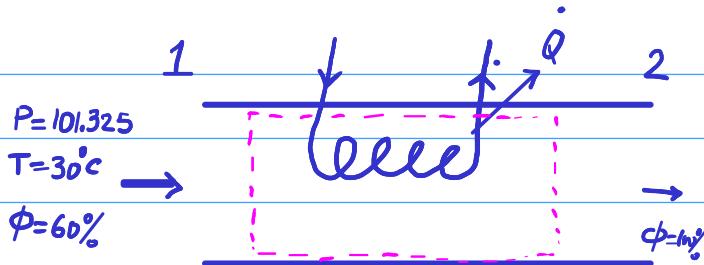
$$m_w = ?, \omega = ?, T_{dp} = ?$$

$$\omega = \frac{0.622 P_w}{P - P_w} = \frac{0.622 \phi P_g}{P - \phi P_g}$$



Ambient air enters a cooling unit

Volume flow rate = 100 L/s



SFEE

$$\dot{Q} - \dot{W} = \dot{m}_a (h_2 + \frac{v^2}{2} + gz)_2 - \dot{m}_a (h_1 + \frac{v^2}{2} + gz),$$

$$\frac{\dot{Q}}{\dot{m}_a} = h_2 - h_1 \Rightarrow \frac{\dot{Q}}{\dot{m}_a} = (62 - 71.5) \text{ kJ/kg of dry air}$$

$$= -9.5 \text{ kJ/kg of dry air}$$

Neglecting KE and PE

$$h_1 = 71.5 \text{ kJ/kg of dry air}$$

$$h_2 = 62 \text{ kJ/kg of dry air}$$

$$v = 0.88 \text{ m}^3/\text{kg of dry air}$$

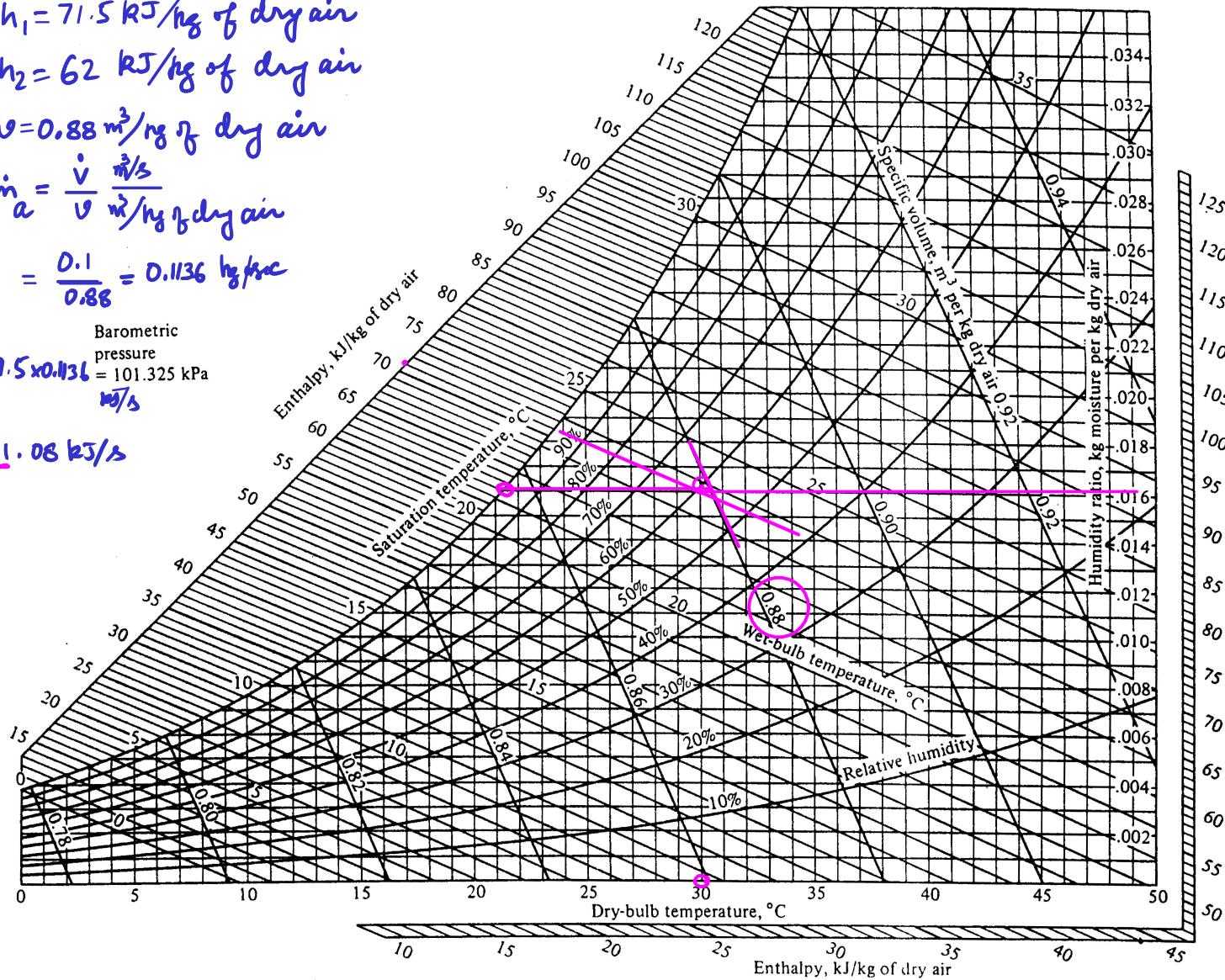
$$\dot{m}_a = \frac{\dot{V}}{v} \text{ kg/s}$$

$$= \frac{0.1}{0.88} = 0.1136 \text{ kg/sec}$$

$$\text{Barometric pressure} = 101.325 \text{ kPa}$$

$$\text{m/s}$$

$$= 1.08 \text{ kJ/s}$$



First law of Thermodynamics

- Control mass system
 - Steady
 - Unsteady

$$\delta Q - \delta W = dU$$

- Control volume

- Steady flow SFEE

- Unsteady flow Charging, discharging

$$\delta Q = TdS$$

$$\delta W = PdV$$

Second law of Thermodynamics

- Two statements
 - Kelvin-Planck Statement \rightarrow Heat Engines
 - Clausius Statement \rightarrow Refrigeration or Heat Pump
- Thermodynamic temperature absolute scale.
- Reversible engine efficiency maximum (Carnot Cycle)
- Clausius Inequality $\oint \frac{dQ}{T} \leq 0$

Entropy

- System and surroundings
- Entropy change of universe ≥ 0

Exergy

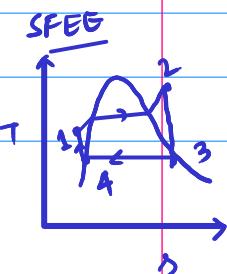
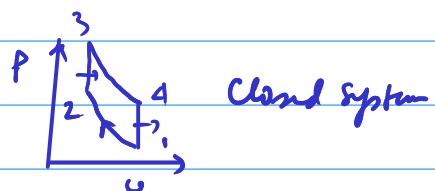
- Maximum work or reversible work (work producing)
- Minimum " " " " (work consuming)
- Closed system or Open system

Cycle

- Gas power cycle
- Vapour power cycle

$$P_1V_1 = C$$

$$P_1V_1 = C$$



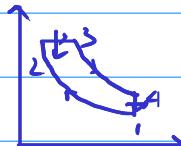
- Refrigeration cycle

$$W_2 = \checkmark$$

$$Q_{23} = C_v(T_3 - T_2)$$

$$W_3 = \checkmark$$

$$Q_{31} = -$$



Monwell relations

Gas mixtures

Air mixture dry air
+
Water vapour

Q-37

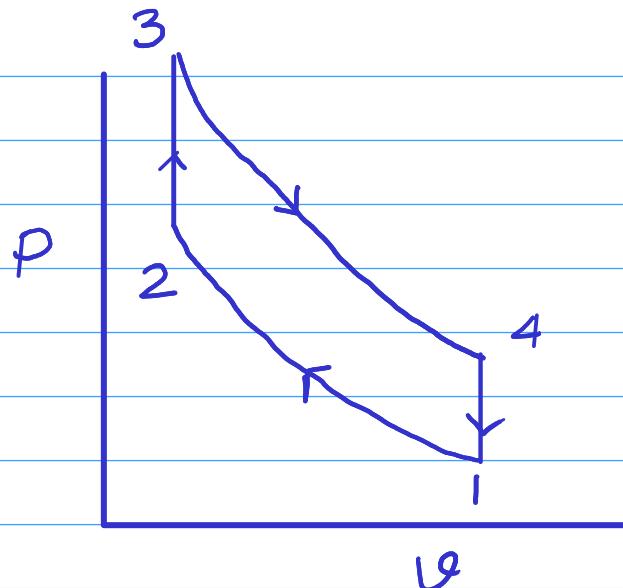
$$\frac{V_1}{V_2} = \frac{V_1}{V_2} = 9.5$$

$$P_1 = 100 \text{ kPa}$$

$$T_1 = 273 + 35 = 308 \text{ K}$$

$$V_1 = 600 \text{ cm}^3$$

$$T_4 = 800 \text{ K}$$



Mean effective pressure (mep)

$$= \frac{W_{\text{net}}}{V_1 - V_2} = \frac{\omega_{\text{net}}}{\vartheta_1 - \vartheta_2}$$

$$\frac{T_2}{T_1} = \left(\frac{\vartheta_1}{\vartheta_2} \right)^{\gamma-1} \quad \gamma = 1.4 \quad T_2 = \checkmark$$

$$\frac{T_3}{T_4} = \left(\frac{\vartheta_3}{\vartheta_4} \right)^{\gamma-1} = \left(\frac{\vartheta_2}{\vartheta_1} \right)^{\gamma-1} \quad T_3 = \checkmark$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \quad P_2 = \checkmark$$

$$P_2 V_2 = R T_2$$

$$P_3 V_3 = R T_3$$

$$q_{\text{in}} = c_v (\vartheta_3 - \vartheta_2) \quad P_3 = \checkmark$$

$$c_v = 0.718 \text{ kJ/kgK}$$

$$q_{\text{out}} = \checkmark$$

$$\frac{V_1}{V_2} = 9.5$$

$$\check{P}_1 \check{V}_1 = m \check{R} \check{T}_1$$

$m_2 \check{v}$

$$V_2 = V$$

$$mep = \frac{W_{net}}{(V_1 - V_2)} = \check{v}$$

7-94

$$\dot{Q} = 110 \text{ W}$$

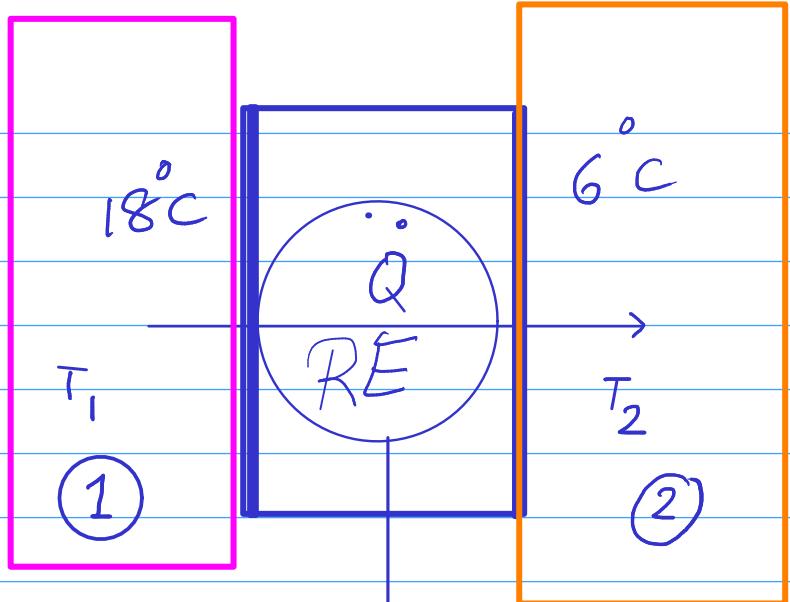
$$\Delta S_1 = \frac{\dot{Q}}{T_1} = \frac{-110}{273+18} =$$

$$\Delta S_2 = \frac{\dot{Q}}{T_2} = \frac{110}{273+6} =$$

$$\Delta S_{\text{universe}} = \Delta S_1 + \Delta S_2$$

$$= 0.016 \frac{W}{K} \quad \checkmark \quad \text{Irreversible.}$$

$$= \left(1 - \frac{279}{291}\right) \times 110$$



$$W = n_{RE} \times \dot{Q}$$

$$\Delta S_{\text{universe}} = 0 \quad \text{Reversible} \quad = 4.536 \text{ W}$$

$$= -V\dot{P} \quad \times \quad \dot{Q}_1 = 110 \quad ; \quad \dot{Q}_L = 110 - 4.536$$

$$\Delta S_{\text{universe}} = 0 \quad - \frac{110}{291} \quad + \quad \frac{110 - 4.536}{279}$$

SFEE for actual

$$h_{2a} + \frac{v_{2a}^2}{2} = h_1 + \frac{v_1^2}{2}$$

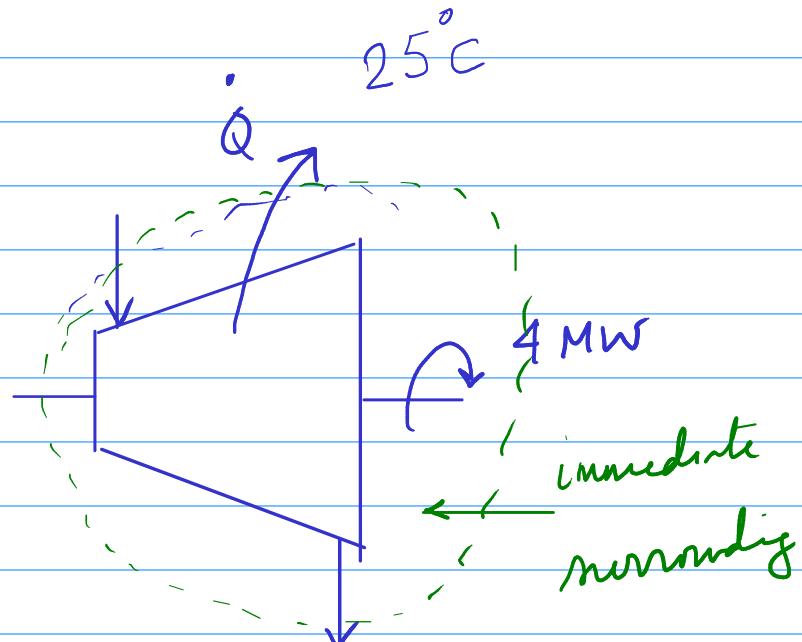
$$\frac{v_{2a}^2}{2} = (h_1 - h_{2a}) + \frac{v_1^2}{2}$$

$$\frac{v_{2a}^2}{2} = 1005 \times (1020 - 763.1) + \frac{80^2}{2}$$

$$= 261384.5$$

$$v_{2a} = \boxed{723 \text{ m/s}}$$

7-143 $m = 25000 \text{ kg/h}$
 $= 25000 / 3600 \text{ kg/s}$
 $= 6.94 \text{ kg/s}$



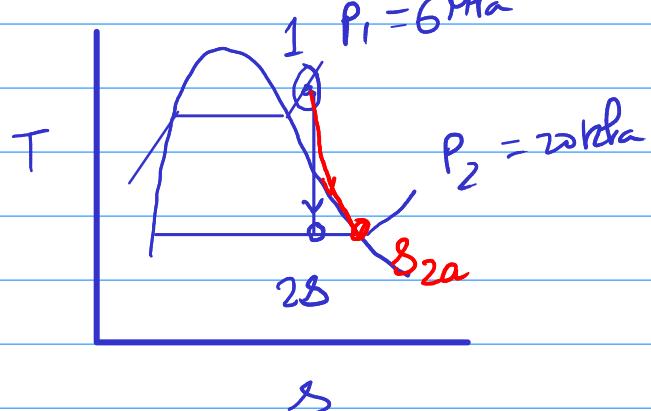
$$P_1 = 6 \text{ MPa}, T_1 = 450^\circ\text{C}$$

$$T_{sat} @ 6 \text{ MPa} = 275.59^\circ\text{C}$$

$$h_1 = 3302.9 \text{ kJ/kg}$$

$$s_1 = 6.7219 \text{ kJ/kg·K}$$

$$s_g @ 20 \text{ kPa} = 7.9073 \text{ kJ/kg·K}$$



$$\dot{\delta}_{23} = \dot{\delta}_1 = 6.7219 \text{ kJ/kg K}$$

$$\dot{\Delta S}_{\text{universe}} = (\dot{\Delta S})_{\text{cv}} + (\dot{\Delta S})_{\text{surrounding}}$$

$$(\dot{\Delta S})_{\text{cv}} = m (\dot{\delta}_{2a} - \dot{\delta}_{23})$$

$$= 6.944 \times (7.9073 - 6.7219) \frac{\text{kJ}}{\text{K}}$$

$$= 8.231 \frac{\text{kJ}}{\text{K}}$$

$$(\dot{\Delta S})_{\text{surrounding}} = \frac{\dot{Q}}{T_{\text{surrounding}}} = \frac{819.1}{298} = 2.749 \frac{\text{kJ}}{\text{K}}$$

$$(\dot{\Delta S})_{\text{universe}} =$$

$$\dot{Q}$$

KE and PE neglected

$$\dot{Q} - \dot{W} = m \left(h + \frac{V^2}{2} + gz \right)_{2a} - m \left(h + \frac{V^2}{2} + gz \right)_1$$

$$h_{2a} = 2608.9 \text{ kJ/kg}$$

$$\dot{W} = 4 \text{ MW} = 4000 \text{ kW}$$

$$\dot{Q} = 4000 + 6.944(2608.9 - 3302.9)$$

$$= 4000 - 4819.1$$

$$= -819.1 \text{ kW}$$

12/3/21

7-119

state 1

$$P_1 = 7 \text{ MPa}, T_1 = 500^\circ\text{C}$$

$$V_1 = 45 \text{ m/s}$$

$$P_2 = 100 \text{ kPa}, V_2 = 75 \text{ m/s}$$

$$\eta_T = 77\% = 0.77$$

$$h_1 = 3411.4 \text{ kJ/kg}$$

$$\delta_1 = 6.8 \text{ kJ/kg}\cdot\text{K}$$

$$\delta_1 = \delta_{28}$$

$$6.8 = \delta_{28}$$

$$h_f @ 100 \text{ kPa} = 1.3028 \text{ kJ/kg}\cdot\text{K}$$

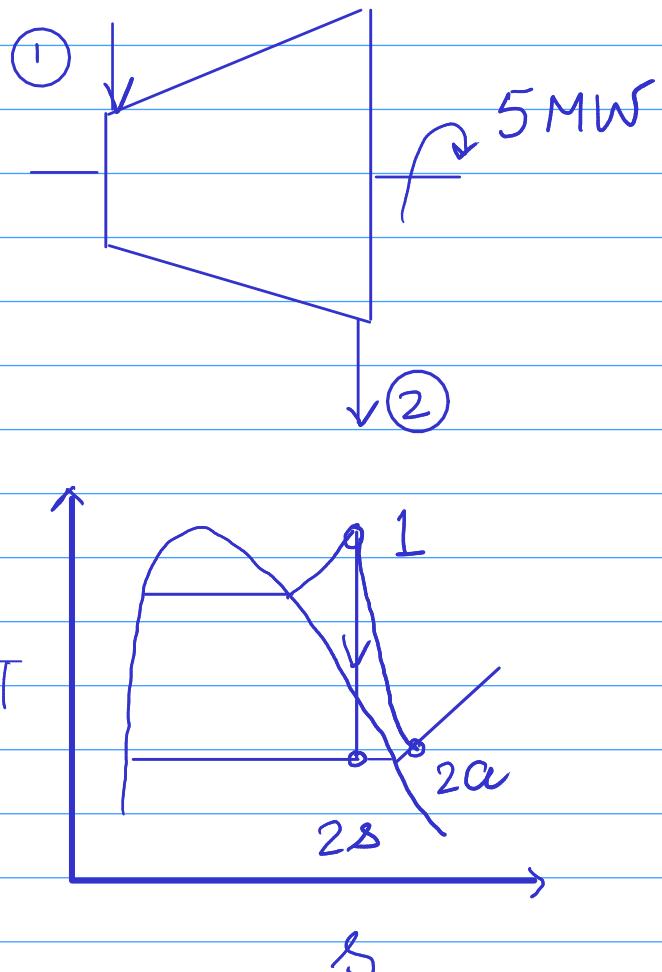
$$h_g @ 100 \text{ kPa} = 7.3589 \text{ kJ/kg}\cdot\text{K}$$

$$6.8 = 1.3028 + x(7.3589 - 1.3028)$$

$$x = 0.91 \quad (0.9077)$$

$$\begin{aligned} h_{28} &= h_f + x h_{fg} = 1.3028 + 0.9077 \times 2257.5 \\ &= 2466.6 \text{ kJ/kg} \end{aligned}$$

$$\eta_T = \frac{\left(h_1 + \frac{V_1^2}{2}\right) - \left(h_{28} + \frac{V_2^2}{2}\right)}{\left(h_1 + \frac{V_1^2}{2}\right) - \left(h_{28} + \frac{V_2^2}{2}\right)}$$



$$0.77 = \frac{(3411.4 + \frac{45^2}{2000}) - (h_{2a} + \frac{75^2}{2000})}{(3411.4 + \frac{45^2}{2000}) - (2466.6 + \frac{75^2}{2000})}$$

$$h_{2a} = 2683.5 \text{ kJ/kg}$$

$$h_g @ 100 \text{ kPa} = 2675.0 \text{ kJ/kg}$$

$h_{2a} > h_g @ 100 \text{ kPa}$ superheated

$$T_{2a} = ? \approx 100.5^\circ\text{C}$$

PE neglected

SFEE

$$\dot{Q} - \dot{W} = \dot{m} \left(h + \frac{V^2}{2} + gz \right)_{2a} - \dot{m} \left(h + \frac{V^2}{2} + gz \right)_1$$

$$-5000 = \dot{m} \left[2683.5 + \frac{75^2}{2000} - 3411.4 - \frac{45^2}{2000} \right]$$

$$\dot{m} = 6.88 \text{ kg/sec}$$

$$\dot{s} = \dot{m} (s_{2a} - s_1)$$

For

turbine $s_{2a} = 7.3611 \text{ kJ/kgK}$

$$\Delta \dot{s} = 6.88 \times (7.3611 - 6.8)$$

$$= 3.86 \frac{\text{RW}}{\text{K}}$$