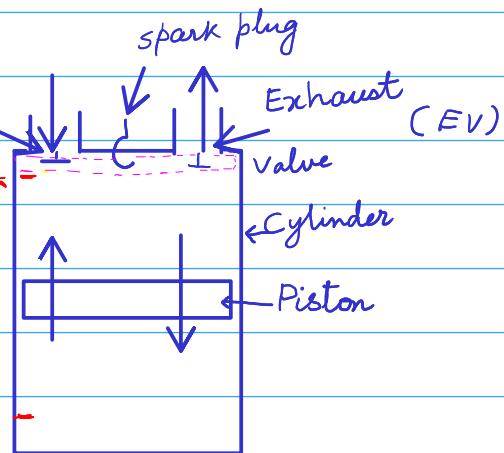


Thermodynamics ME22002 3-1-0-4

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 ↑  $B \rightarrow A$

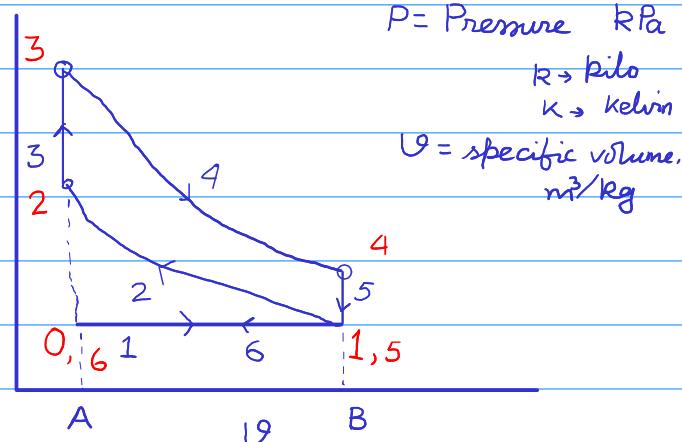
Volume is decreased. Compression

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

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

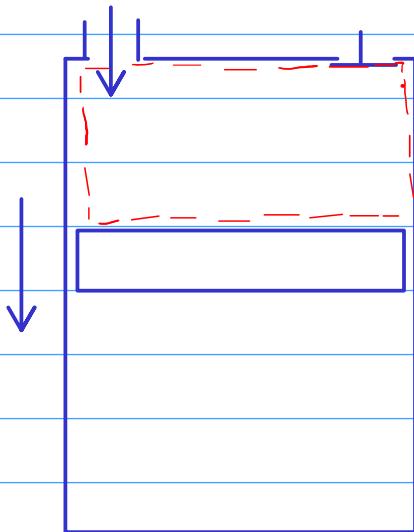
Process 1 starts

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

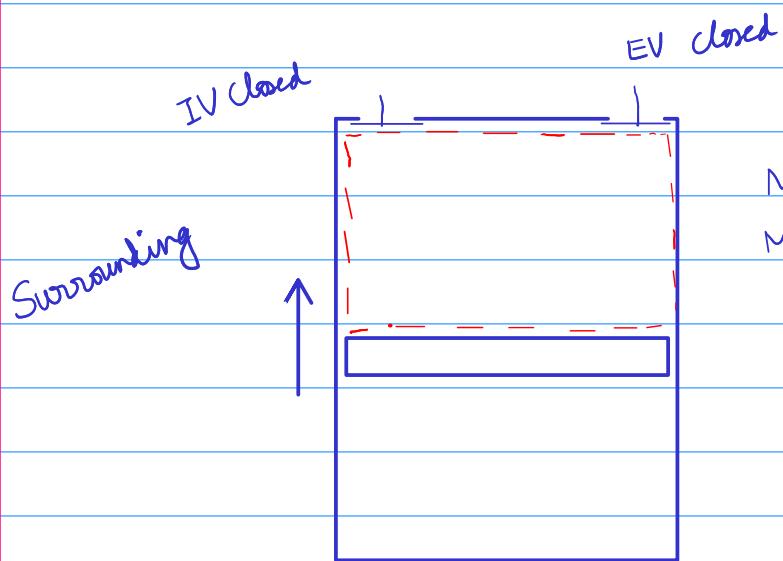
$$2 \quad P =$$

$r_c = \text{compression ratio}$

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

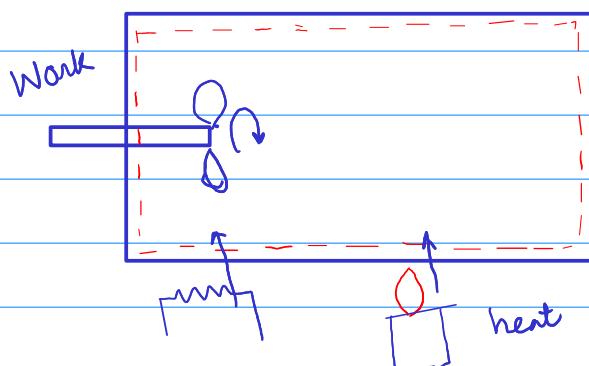


- - - System boundary  
 mass is crossing the boundary  
 control volume (cv)  
 Open system

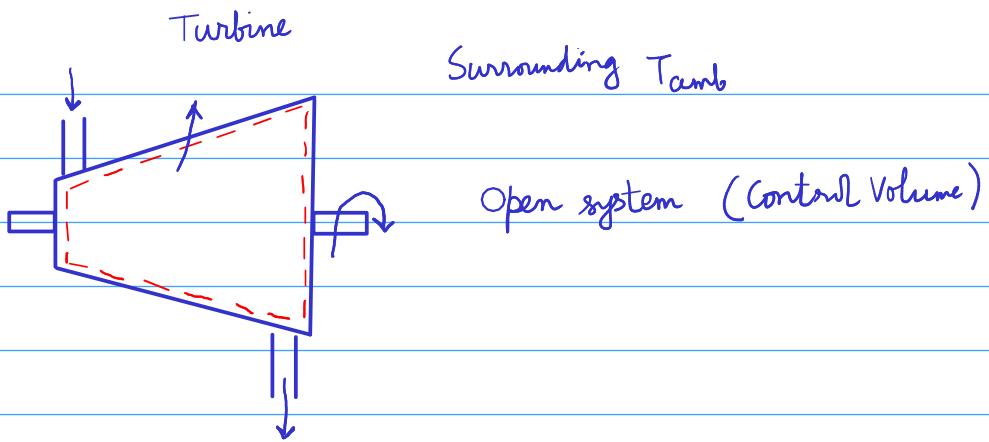


- - - Boundary  
 Mass is not crossing the boundary  
 Mass is fixed.  
 Control mass system  
 Closed system

Energy can cross the boundary  
 Work or heat



Closed system



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, m<sup>3</sup>

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, m<sup>3</sup>

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

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

$$PV = RT$$

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

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

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

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 Energy

mass ×

CONTROL VOLUME

ISOLATED SYSTEM

Energy, mass ×

neither mass

nor energy can cross  
the boundary

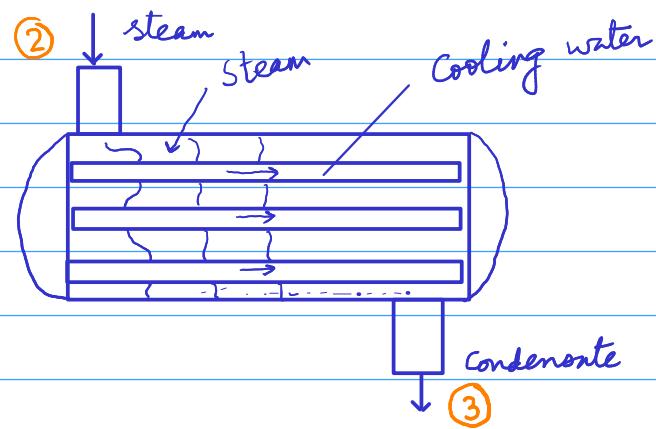
Superheated steam

--- boundary

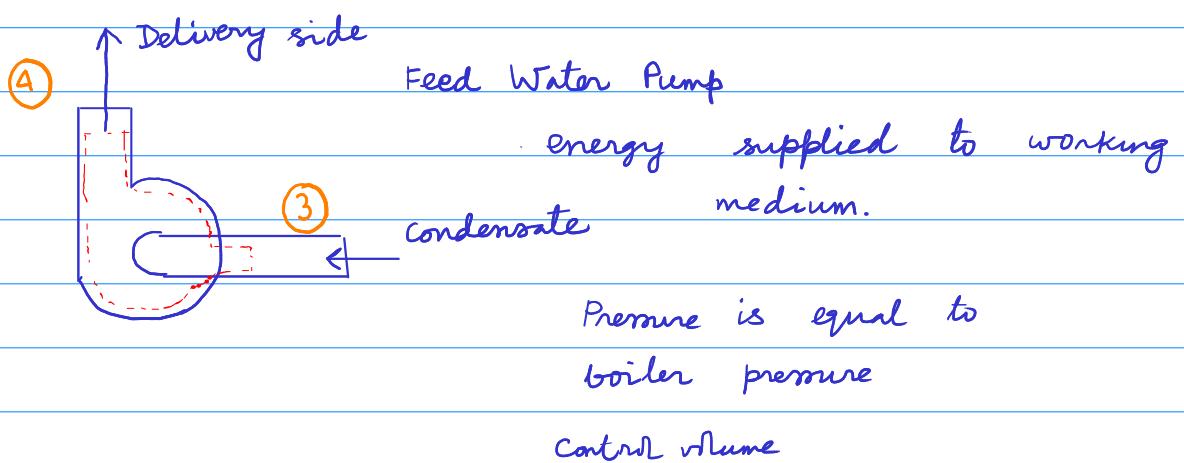
CONTROL VOLUME

steam at saturated

wet steam

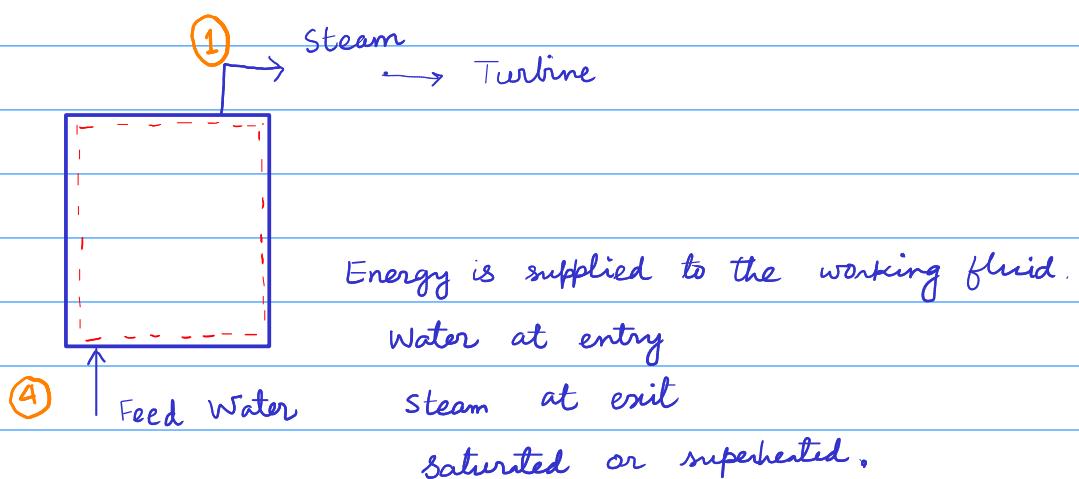


Phase change process  
steam to water



Pressure is equal to  
boiler pressure

control volume



Water at entry

steam at exit

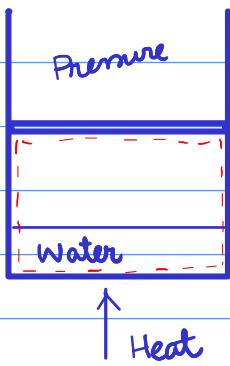
saturated or superheated.

CYCLE IS COMPLETE

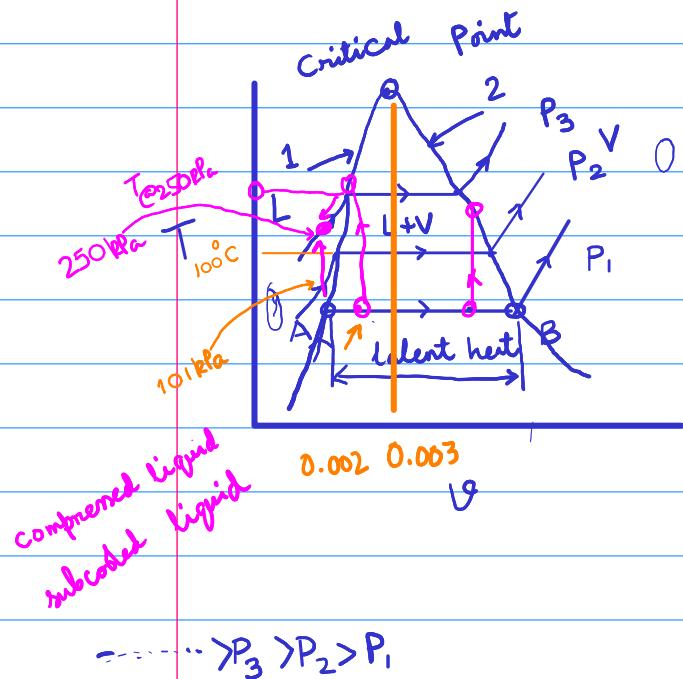
Process 1	Turbine	Work Produce
" 2	Condenser	Devices → Heat extraction
" 3	Feed Water Pump	→ Work consumption
" 4	Boiler	→ Heat addition

14/1/21

## Property of water-vapour



- 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  $T$  temperature,  $^{\circ}\text{C}$

x-axis  $v$  specific volume,  $\text{m}^3/\text{kg}$

A = location at saturated liquid,  $v = 0$

B = location at " vapour,  $l = 0$

Between A and B, mixture of liquid and vapour.

$x = 0$  at A dryness fraction

$= 1$  at B quality of steam

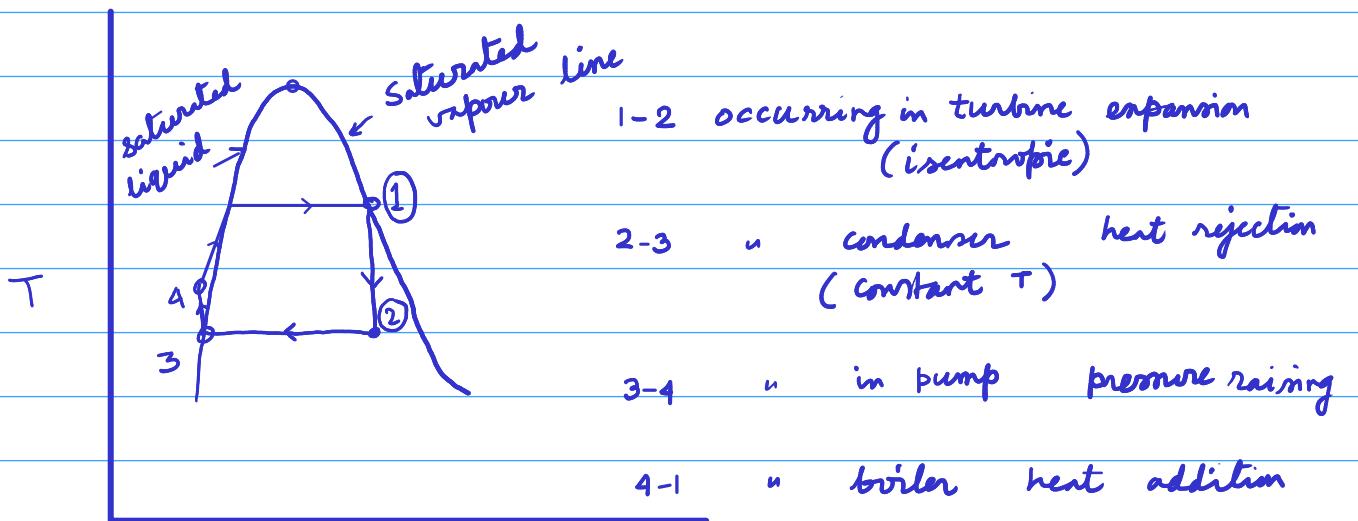
Vapour dome

1  $\rightarrow$  Saturated liquid line

2  $\rightarrow$  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.

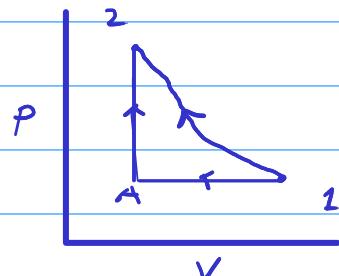
$$W_2 = \int_1^2 PdV$$

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  $PV^n = \text{constant}$

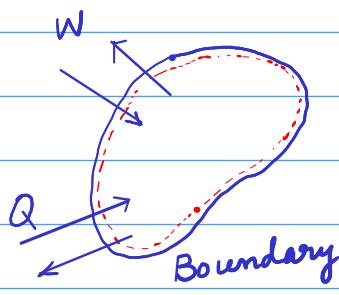
$$W_2 = \int_{V_1}^{V_2} PdV = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

## 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

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

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

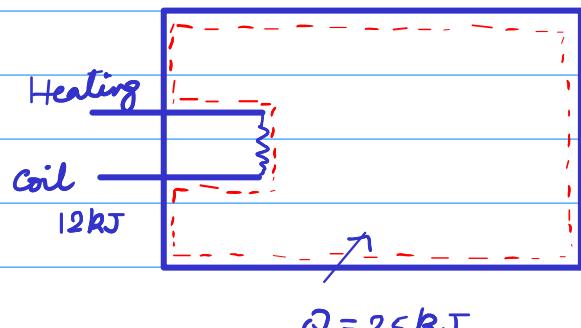
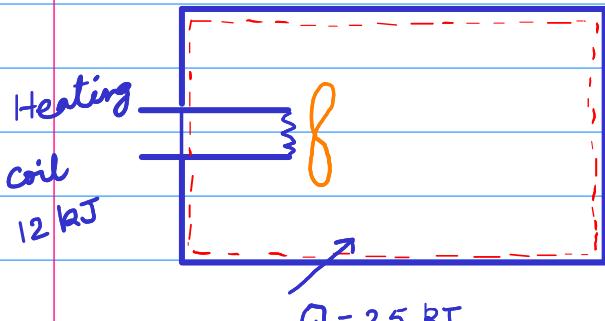
$$q_v = \frac{Q}{m} \text{ kJ/kg}$$

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

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

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

Intensive properties  $q, \omega, u, v, p, T$



$$Q - W = \Delta U$$

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

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

$$Q - W = \Delta U$$

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

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

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

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

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

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

Process is isentropic.

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

$$\gamma = 1.4$$

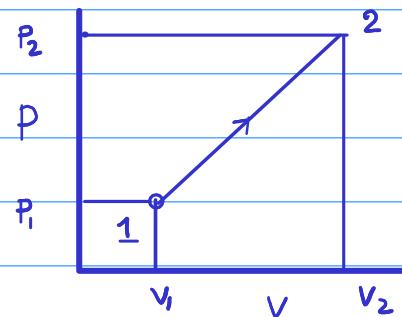
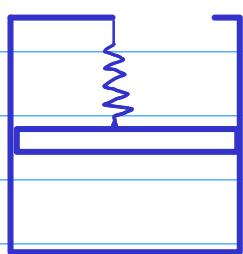
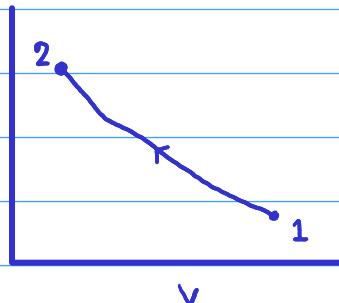
$$P_2, T_2, W_2$$

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

$$2020.73$$

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

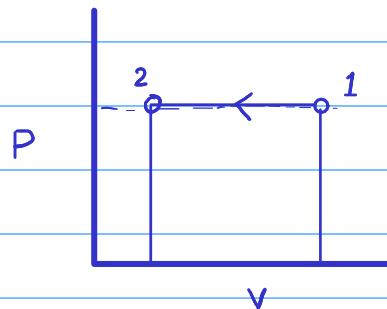
$$W_2 = -410 \text{ J}$$



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

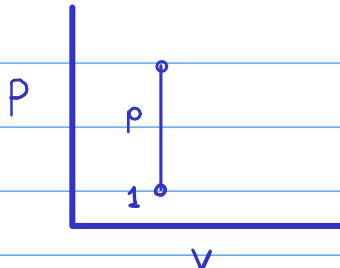
Constant pressure

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

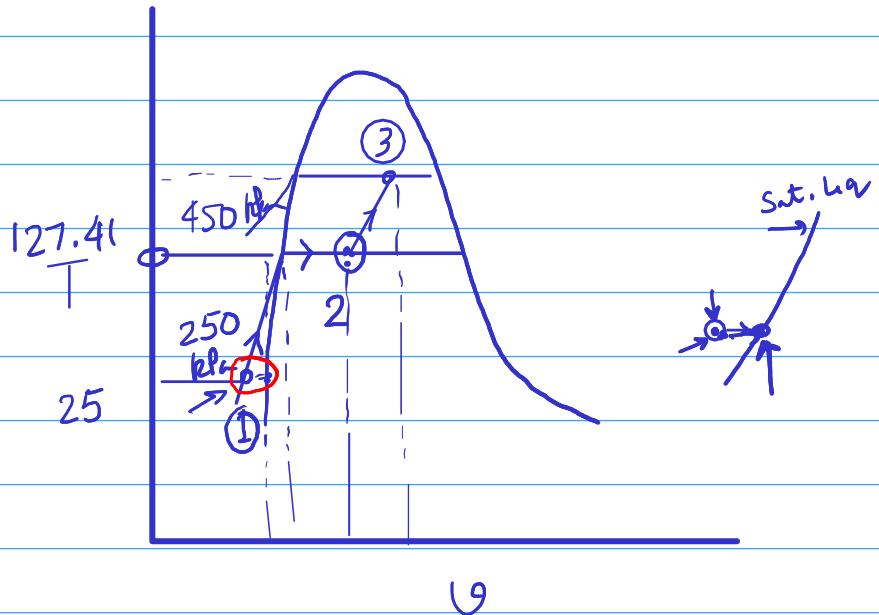


Constant volume

$$W_2 = 0$$



20/1/21



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

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

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

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

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

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

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

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

$$0.001003 < 0.004 < 0.71873$$

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

$$x_2 = \checkmark$$

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

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

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

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

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

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

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

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

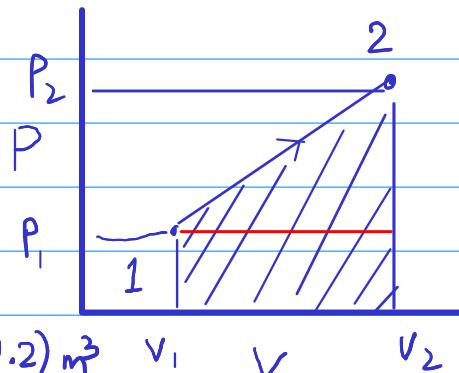
+ sign work is done by the system.  
boundary work

21 | 1 | 21 4-114

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

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

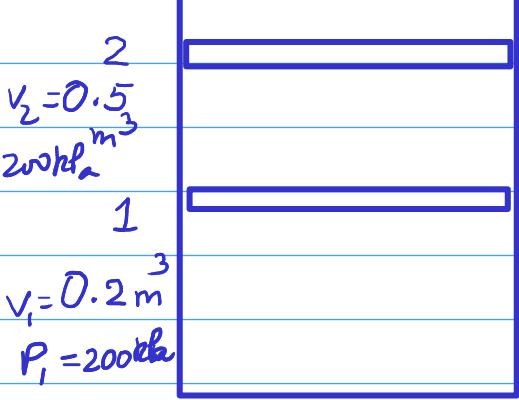
$$= 150 \text{ kJ}$$



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

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

$$= 60 \text{ kJ}$$



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

$$= 90 \text{ kJ}$$

4-36

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

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

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

$$= 4.731 \text{ kg}$$

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

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

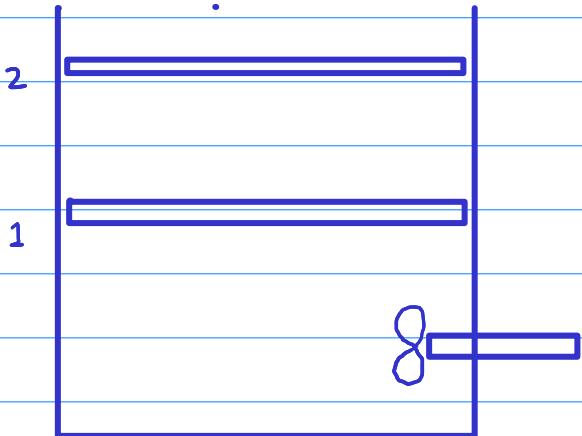
$$Q = +ve$$

$$Q - W = \Delta U$$

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

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

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



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

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

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

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

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

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

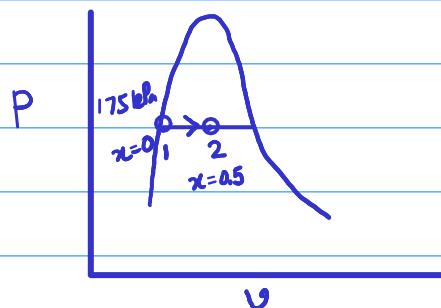
$$Q =$$

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

$$I = 8A$$

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

$$V = \text{volt}$$



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

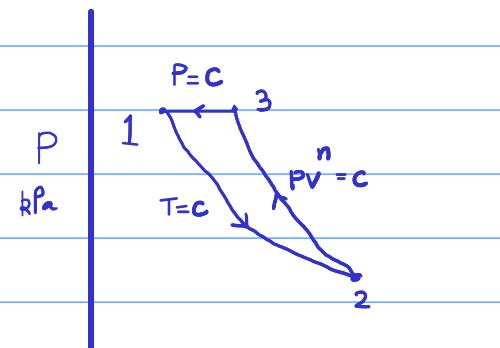
state 1

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

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

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

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

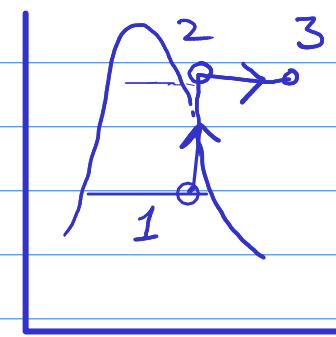
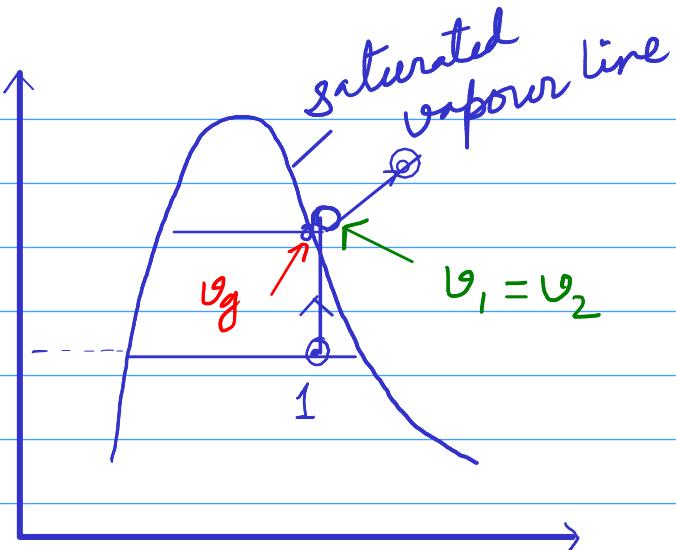
$$m = 5 \text{ kg}$$

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

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

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

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



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

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

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

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

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

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

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

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

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

$$P_1 V_1 = m R T_1$$

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

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

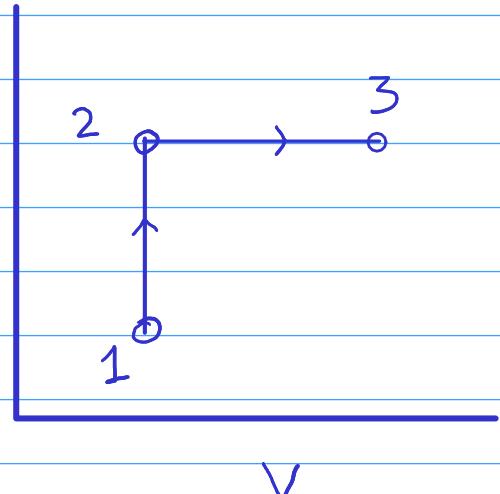
state 2

$$V_2 = 1.2915 = V_1$$

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

$$P_2 V_2 = m R T_2$$

$$P_1 V_1 = m R T_1$$



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

state 3

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

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

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

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

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

$$= 516.6 \text{ kJ}$$

$\gamma, c_p, c_v$  ---

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

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

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

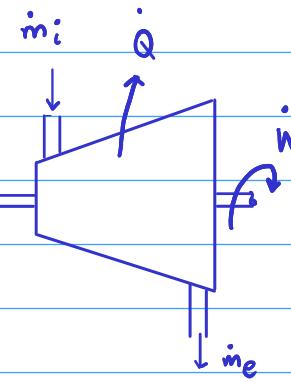
will be supplied.

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

### CONTROL VOLUME

⇒ Mass balance

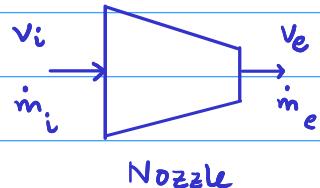
⇒ Energy balance



Reynolds Transport Theorem (RTT)

Turbine

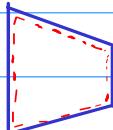
Steady Flow Energy Equation  
(SFEET)



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

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

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

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

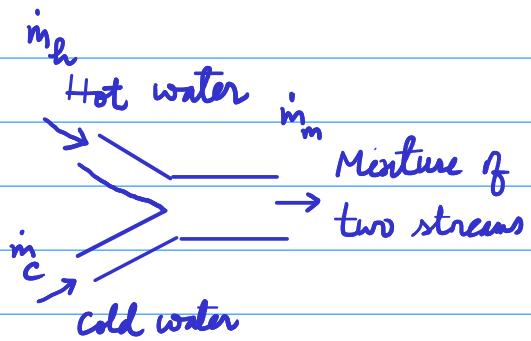
steady flow,  $\frac{d}{dt}(PdV) = 0$

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

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.

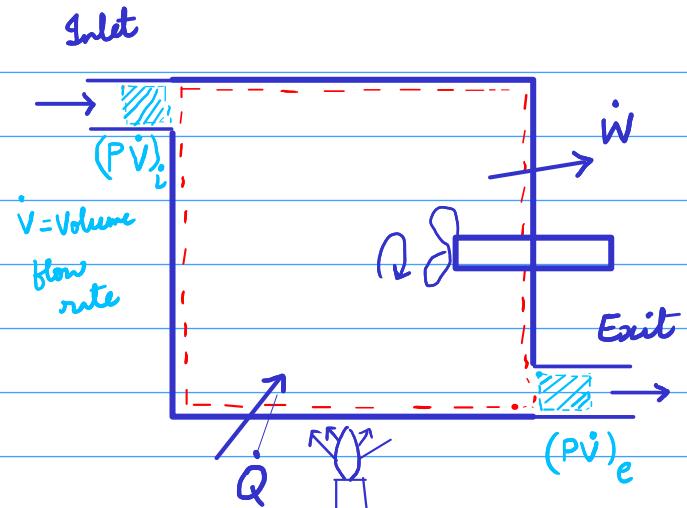
$$\sum \dot{Q} - \sum \dot{W} = \frac{d}{dt} \int_{CV} p(u + \frac{v^2}{2} + gz) dV + \sum \dot{m}_e(h + \frac{v^2}{2} + gz)_e - \sum \dot{m}_i(h + \frac{v^2}{2} + gz)_i$$

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

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

## Steady Flow Energy Equation

SFEE



$$\text{Boundary work rate} = p\dot{V} = \dot{m}(PV)$$

$\dot{V} = \frac{\dot{V}}{\dot{m}} = \frac{m^3/\text{sec}}{kg/\text{sec}} = \frac{m^3}{kg}$

$$\dot{V} = \frac{\dot{V}}{\dot{m}} = \frac{m^3/\text{sec}}{kg/\text{sec}} = \frac{m^3}{kg}$$

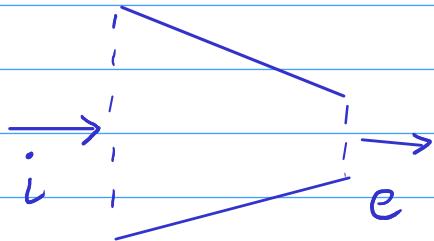
$X^0 K$   
 $\checkmark K$

5-35

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

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

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



$$P_i = P_i R T_i$$

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

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

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

$$A_i = 2A_e$$

Mass conservation equation, steady flow

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

$$P_i A_i V_i = P_e A_e V_e$$

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

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

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)

$$P_e = P_e R T_e$$

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

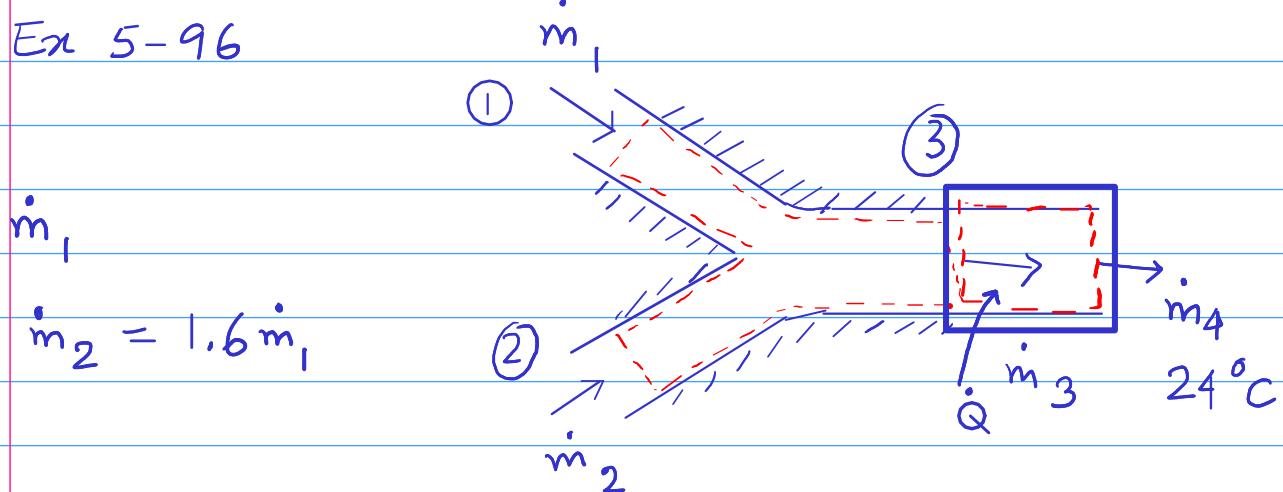
$$= 329.7 \text{ kPa}$$

(b)

## Problem Set 02

28/1/21

Ex 5-96



Mass conservation. Assumption is steady flow.

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

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

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

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

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

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

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

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

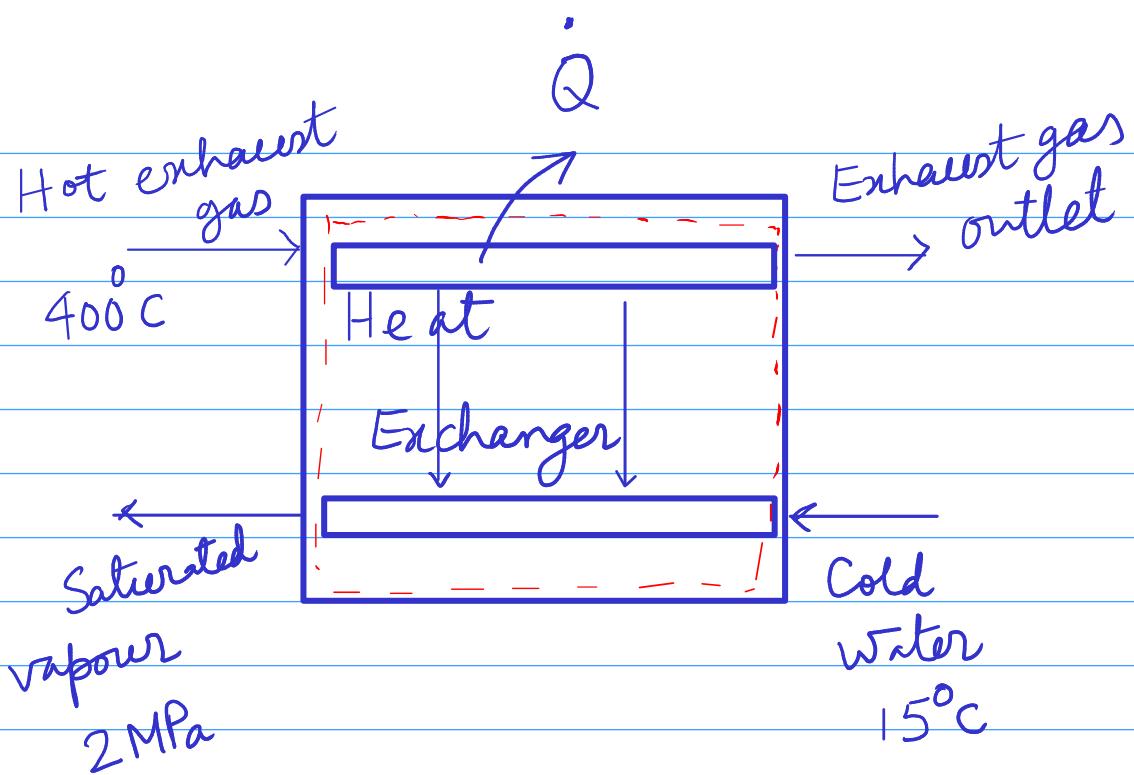
$$P_1 \dot{V}_1 = \dot{m}_1 R T_1$$

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

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

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

~~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  $15^\circ\text{C}$

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

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

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

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

$h = C_p T$  for gas

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

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

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

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

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

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

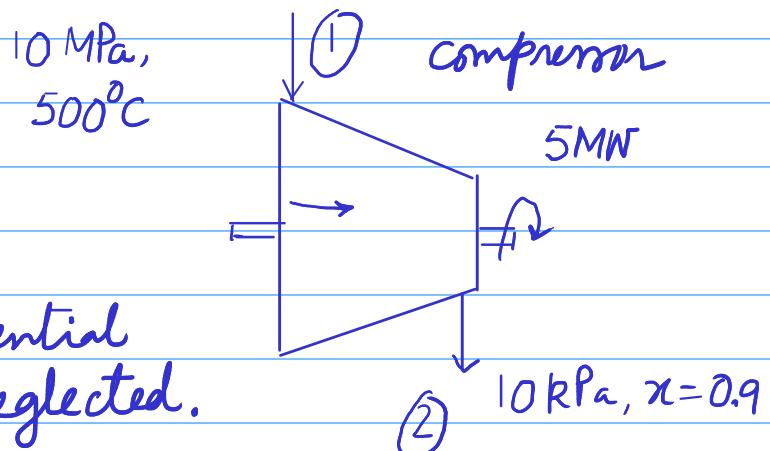
$$\dot{Q}_w = \dot{m}_w \times (h_{we} - h_{wi}) = 0.035 \times (2798.3 - 62.982) \text{ kJ/sec}$$

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

5.51

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

kinetic and potential energies are neglected.

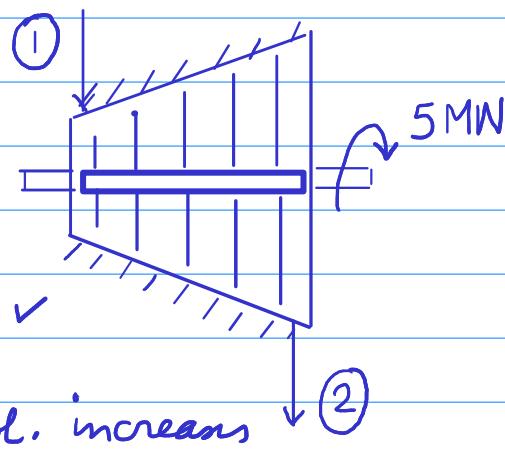


$$\begin{aligned} \dot{Q} - \dot{W} &= \dot{m}_2 \left( h_2 + \frac{V^2}{2} + gz_2 \right) - \\ &\quad \dot{m}_1 \left( h_1 + \frac{V^2}{2} + gz_1 \right), \end{aligned}$$

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

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

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,  $m_e = 0$

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

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

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

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

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

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

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

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

$$= 191.81 + 0.9 \times 2392.1$$

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

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

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

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

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

$500^\circ \text{C}$  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

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

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

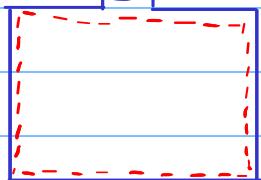
Unsteady Flow



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  $m_2$

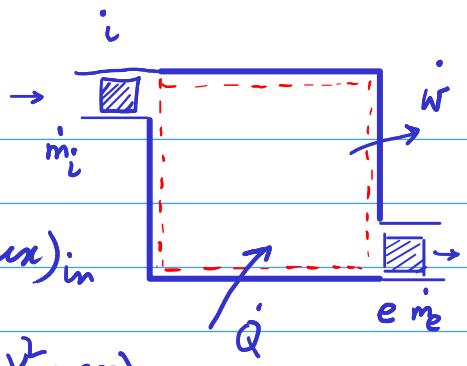
$$0 = (m_2 - m_i) + m_e - m_i$$

$$m_2 - m_i = m_i - m_e$$

4/2/21

RTT

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

 $\forall$  = Volume

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

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

$$\dot{Q} - (w_e + w_i) = \frac{d}{dt} \int_C p(u + \frac{v^2}{2} + gz) dV + \dot{m}_e(u + \frac{v^2}{2} + gz)_e - \dot{m}_i(u + \frac{v^2}{2} + gz)_i$$

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

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

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

Energy  
Equation:

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

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:

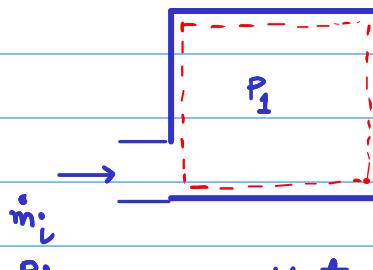
$$\frac{dm}{dt} = \frac{d}{dt} \int_C p \cdot 1 \cdot dV + \dot{m}_e - \dot{m}_i$$

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

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

Integrate between 1 and 2

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



$\dot{m}_i$  = mass flowrate at inlet

$P_i$  = Pressure of the pipeline

$P_1$  = 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

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

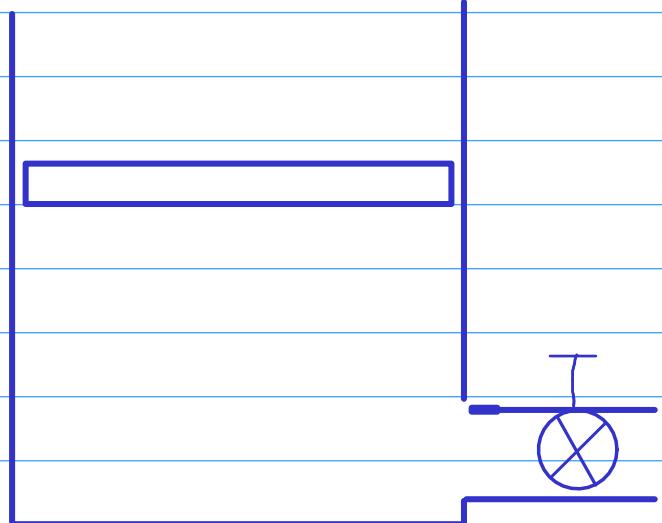
5-131 State 1

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

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

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

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

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

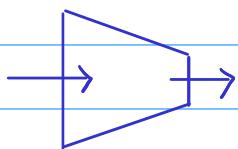
$$m_2 = \frac{3168.1 - 1825.67}{3168.1 - 2706.3}$$

$$= 29.07 \text{ kg}$$

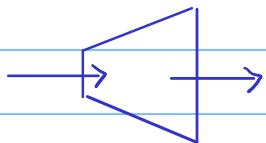
$$m_i = m_2 - m_1 = (29.07 - 10) \text{ kg} = 19.07 \text{ kg}$$

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

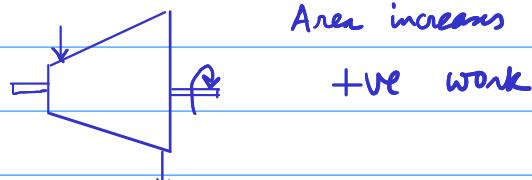
Nozzle



Diffuser

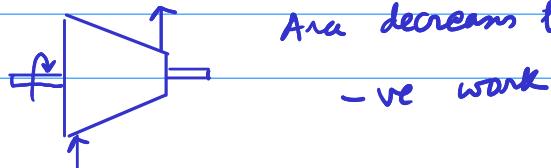


Turbine



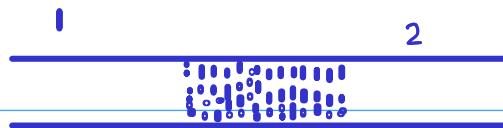
Area increases to accommodate increase specific volume.

Compressor



Area decreases to accommodate decrease in specific volume.

## Throttling process



diameter comfort

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

$$h_2 = h_1$$

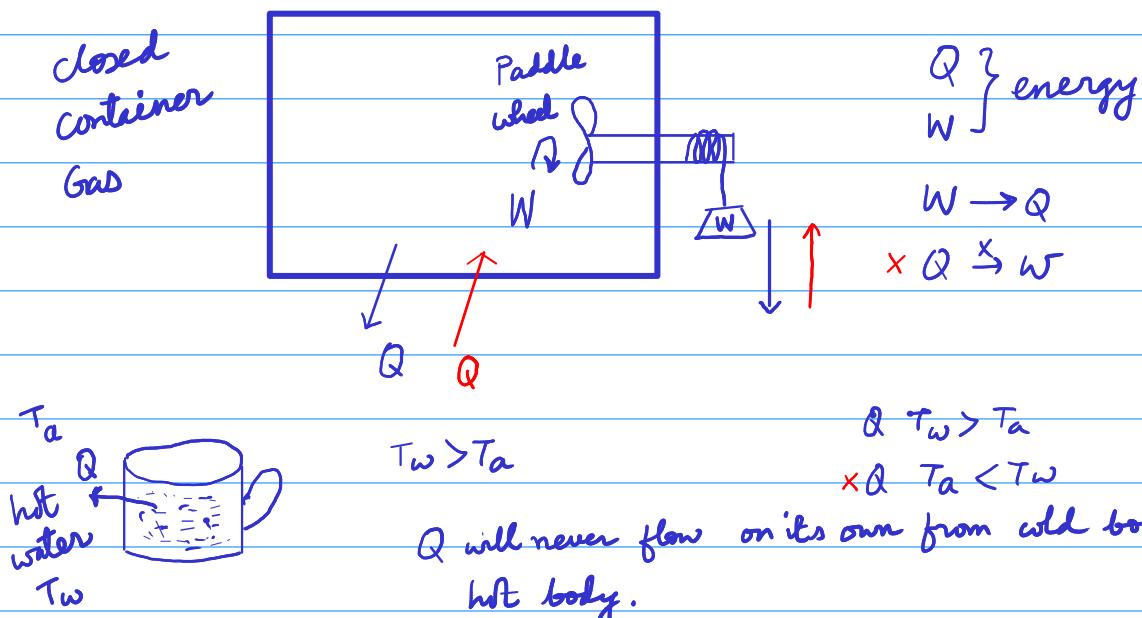
$$u_2 + p_2 v_2 = u_1 + p_1 v_1$$

## 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

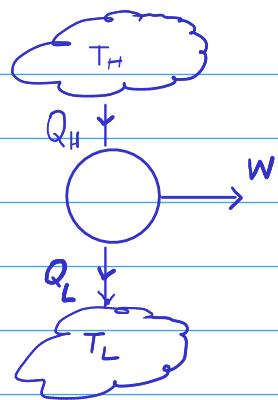
or we withdraw - - - - -

the temperature of the reservoir does not change.

Hot reservoir or high temperature reservoir ( $T_H$ )

Cold " low " "  $(T_L)$

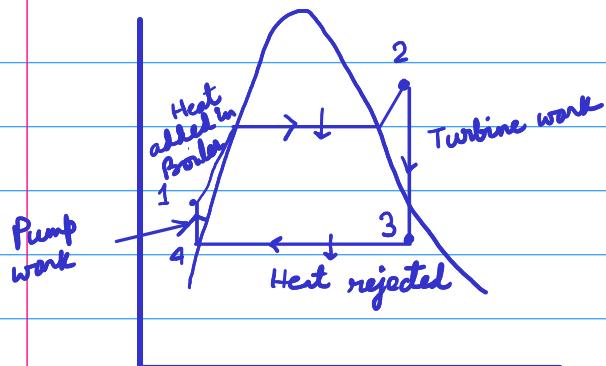
Device  
Heat Engine  
Petrol engine  
Thermal power plant



A.C.

$Q_H$  cannot be completely converted to work.

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



Power plant cycle

$1 \rightarrow 2$   $Q_H$

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

$2 \rightarrow 3$

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

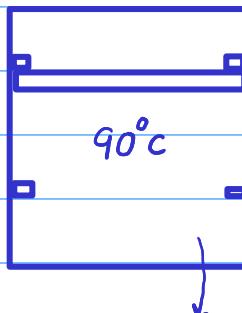
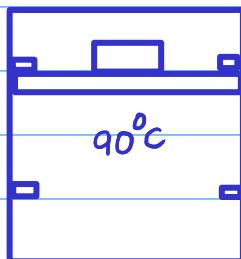
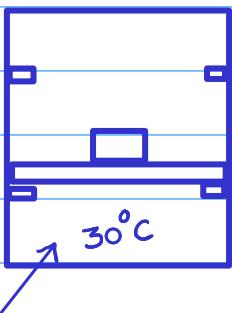
$3 \rightarrow 4$   $Q_L$

$W_p$  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.

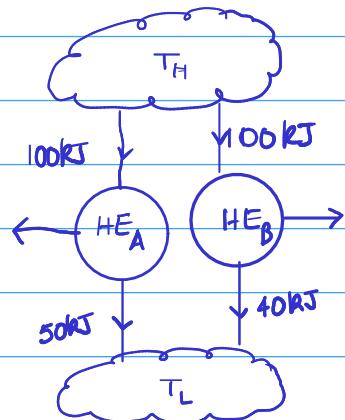
$Q_H$

$W_{net}$

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

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

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



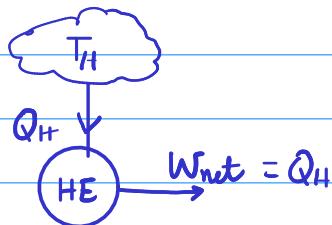
$$\eta_A = 1 - \frac{50}{100} = 0.5 = 50\%$$

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

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

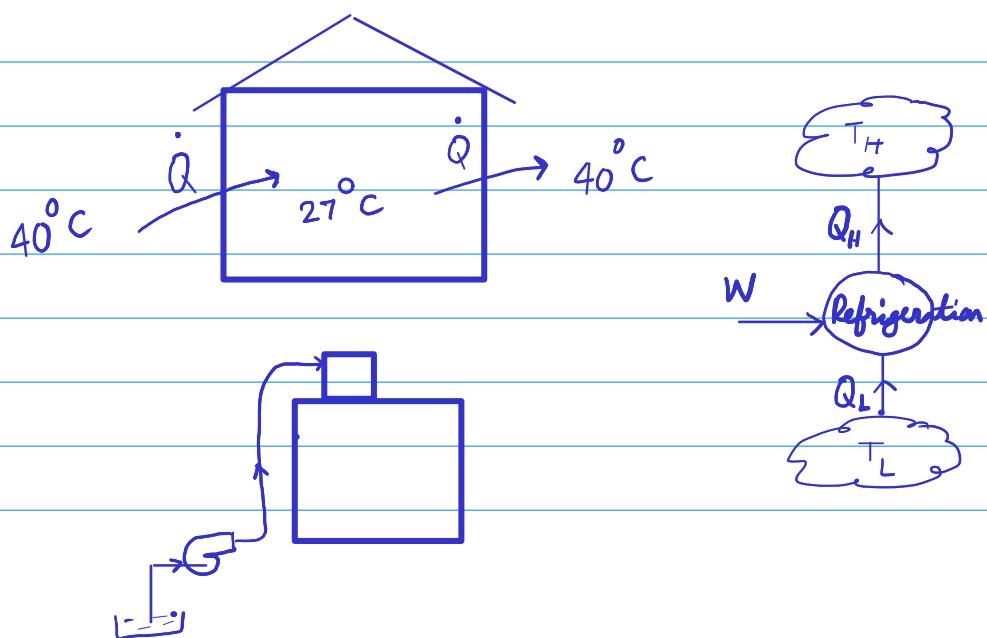
Work is a higher grade energy.

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.

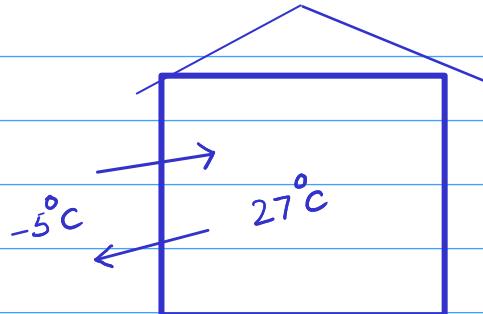
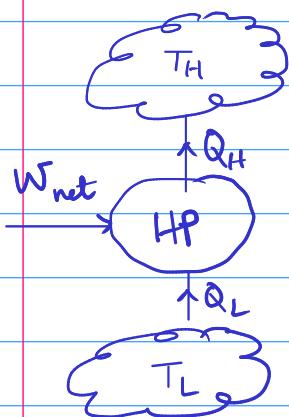


Desired objective  $Q_L$

Energy to be supplied  $W$

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

COP = Coefficient of performance



Desired objective =  $Q_H$

Energy to be supplied =  $W_{\text{net}}$

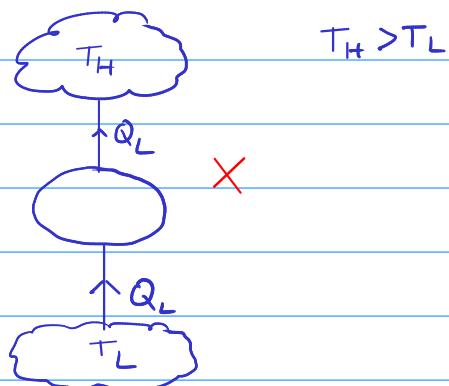
$$COP_{\text{HP}} = \frac{Q_H}{W_{\text{net}}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

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

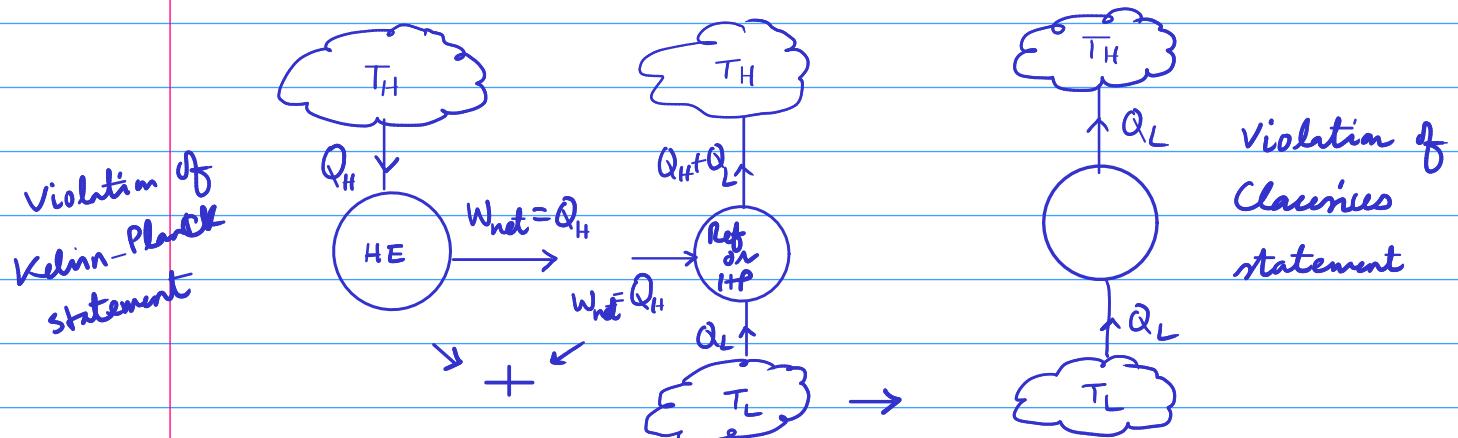
HP = Heat pump

### 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.

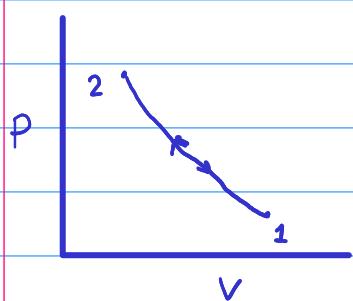


⇒ Violation of one statement leads to the violation of another statement.



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

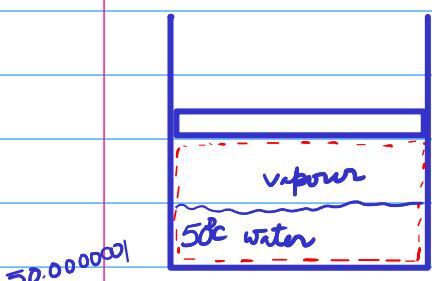
Why : Because all the processes are reversible process.



Process 1→2

Another process 2→1 which is reverse of Process 1→2

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



or infinitesimal small difference

Externally reversible

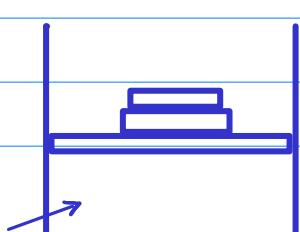
Internally reversible

{ Thermal

Equilibrium

Mechanical equilibrium

Chemical equilibrium.



Reversible Process

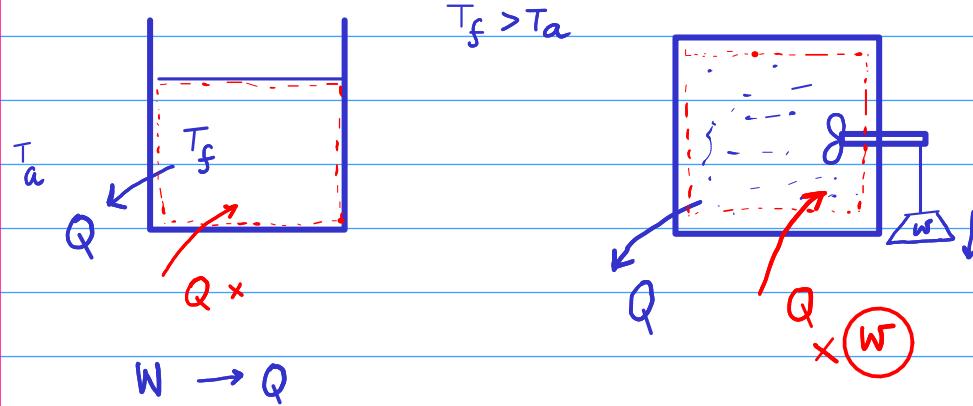
*Thermodynamics: An engineering approach*

*Y.A. Cengel and M.A. Boles*

*McGraw Hill Education (I) Pvt. Ltd.*

*Seventh edition*

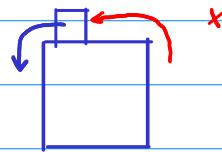
10/2/2021



$Q \rightarrow W$  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)



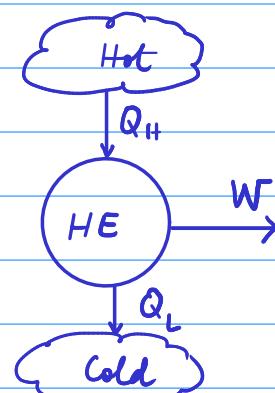
Heat engine  $\rightarrow$  Thermal Power Plant

Boiler

Turbine +ve

Condenser

Pump -ve



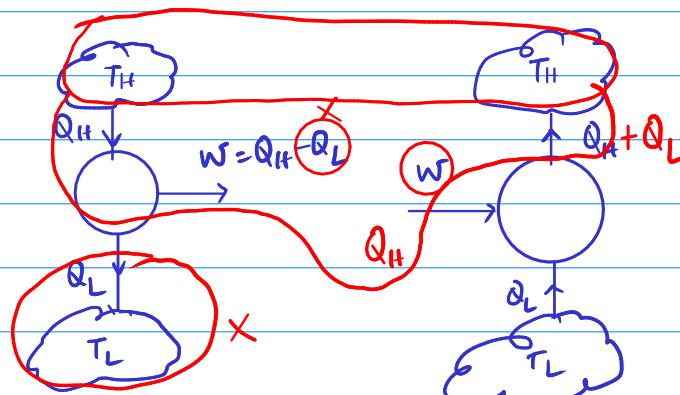
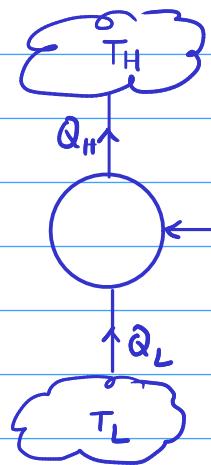
Reverse Heat engine

$Q_L \rightarrow$  Refrigeration

$Q_H \rightarrow$  Heat Pump

Clausius statement

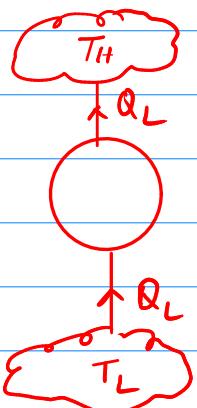
Violation of one statement leads to violation of other statement



$$W = Q_H - Q_L$$

$$Q_H = W + Q_L$$

Violation of  
Clausius  
statement

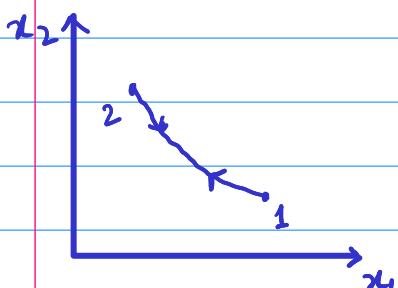


$$\eta_{th} = \frac{W_{net}}{Q_H} \quad \eta_{th} = \text{Thermal efficiency}$$

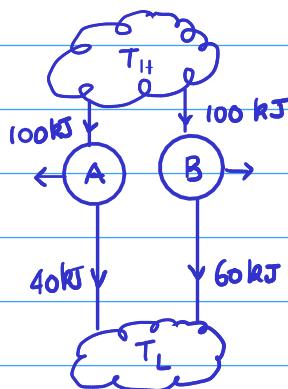
$$= \frac{Q_H - Q_L}{Q_H}$$

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

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



$$\eta_{th} = 1 - \frac{Q_L}{Q_H} \quad \text{when is maximum?}$$



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

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

A better than B

Reversible heat engine

Reversible processes

$$T_H = c$$

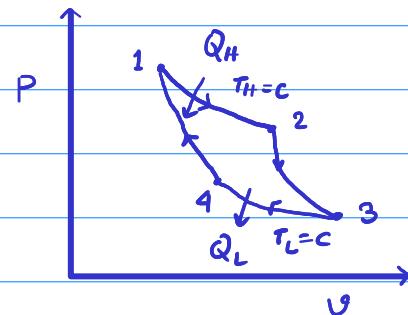
Carnot engine

$$s = c$$

Carnot cycle

$$T_L = c$$

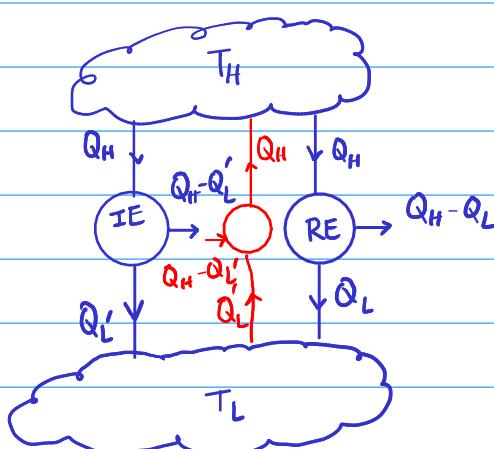
$$s = c$$



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

$$\eta_{th,A} < \eta_{th,RE} \quad \text{Possible}$$

$$\eta_{th,A} > \eta_{th,RE} \quad \text{Not possible.}$$



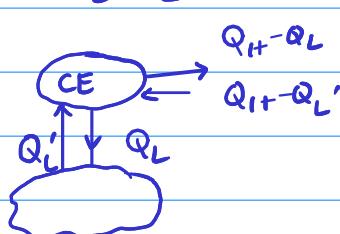
$$\eta_{IE} > \eta_{RE}$$

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

$$Q_L' < Q_L$$

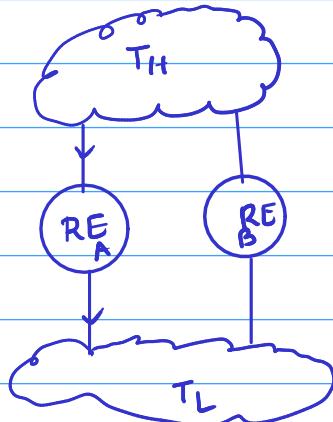
$$Q_L - Q_L'$$

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



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.

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

$T$  → Absolute temperature, K

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

equally applicable to reversible and irreversible cycle.

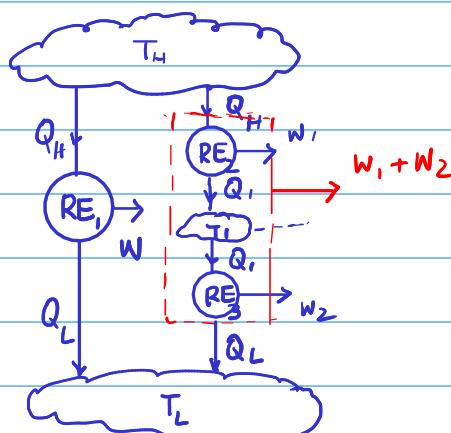
$$= 1 - \frac{T_L}{T_H} \quad \text{cycle is reversible only.}$$

17/2/21

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

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

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



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

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

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

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

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

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

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

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

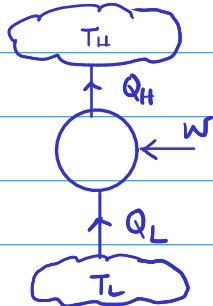
Equally holds good whether the cycle is reversible or irreversible.

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

$\frac{Q_L}{\dot{Q}_H} = \frac{T_L}{T_H}$  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



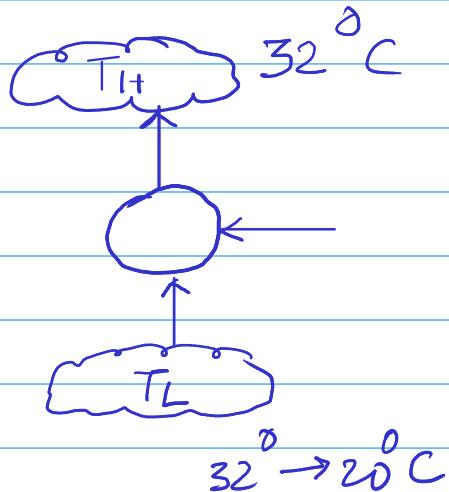
HP = Heat pump

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

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

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

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



$T_L = \text{Inside temperature}$   
 $\text{desired}$

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

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

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

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

$$= 6912 \text{ kJ}$$

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

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

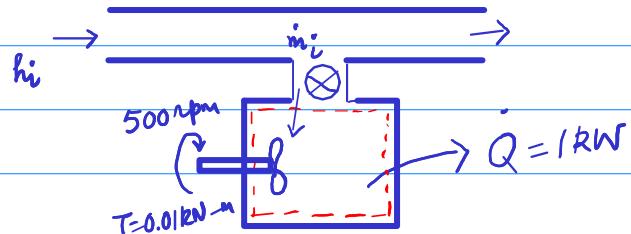
18/2/2021

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

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

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

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



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.

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

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

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

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

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

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

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

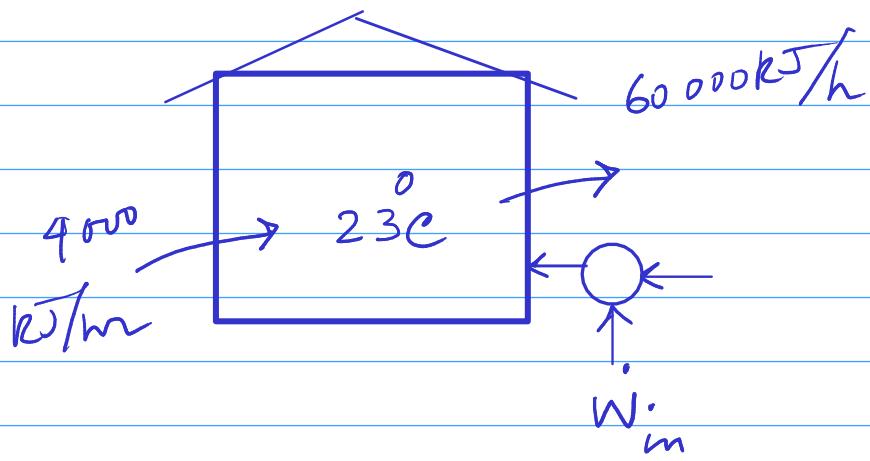
$$\dot{m}_w = 2 \text{ kg}, \quad \frac{dm_w}{dt} = 0.1143 \text{ kg/s}, \quad u_{av} = 2510 \text{ kJ/kg}$$

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

Tomorrow, you give me the solution to this problem

6-51

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

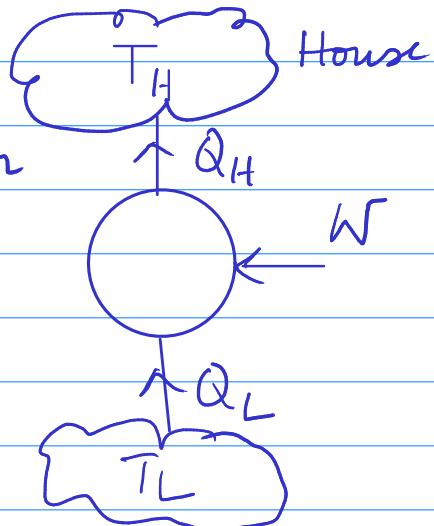


$$\dot{W} = \frac{\dot{Q}_H}{COP}$$

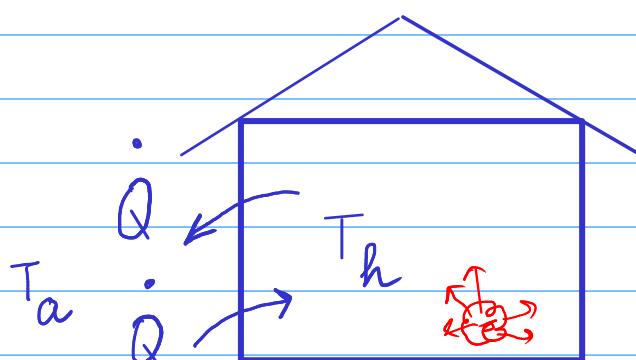
$$\dot{Q}_H = (60000 - 4000) \text{ kJ/h}$$

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

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



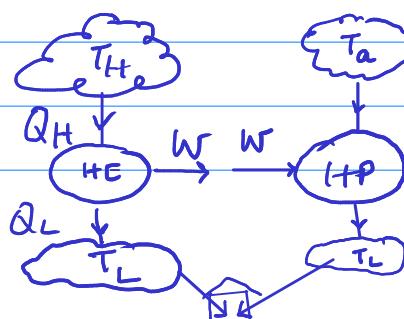
$$\dot{W} = \frac{140}{9 \times 2.5} = \frac{56}{9} \text{ kW} = 6.22 \text{ kW}$$



$T_h$  = Temperature of house

$T_a$  = Temperature of ambient surroundings

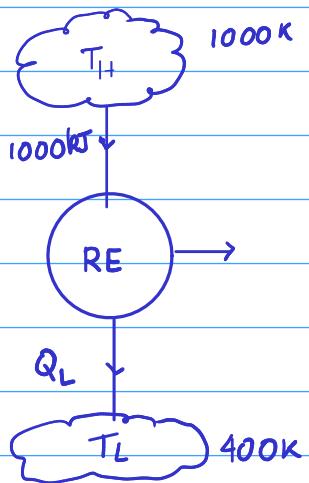
$$\dot{Q} = m \times CV$$



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

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

$$T_L = T_h$$



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

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

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

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

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

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

$= 450, 500, 550 \checkmark$

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

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

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

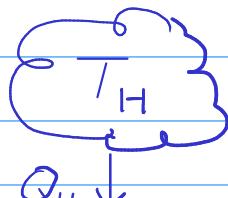
$$\eta_{th,RE} = 1 - \frac{T_L}{T_H} = 1 - \frac{400}{1000} = \frac{600}{1000} = 0.6 \text{ or } 60\%$$

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

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

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

19/2/2021



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

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

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

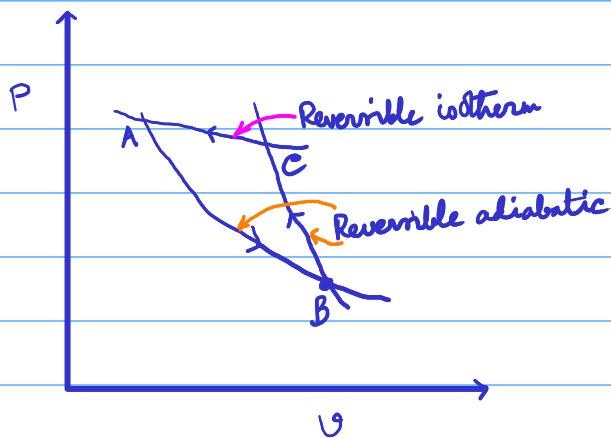
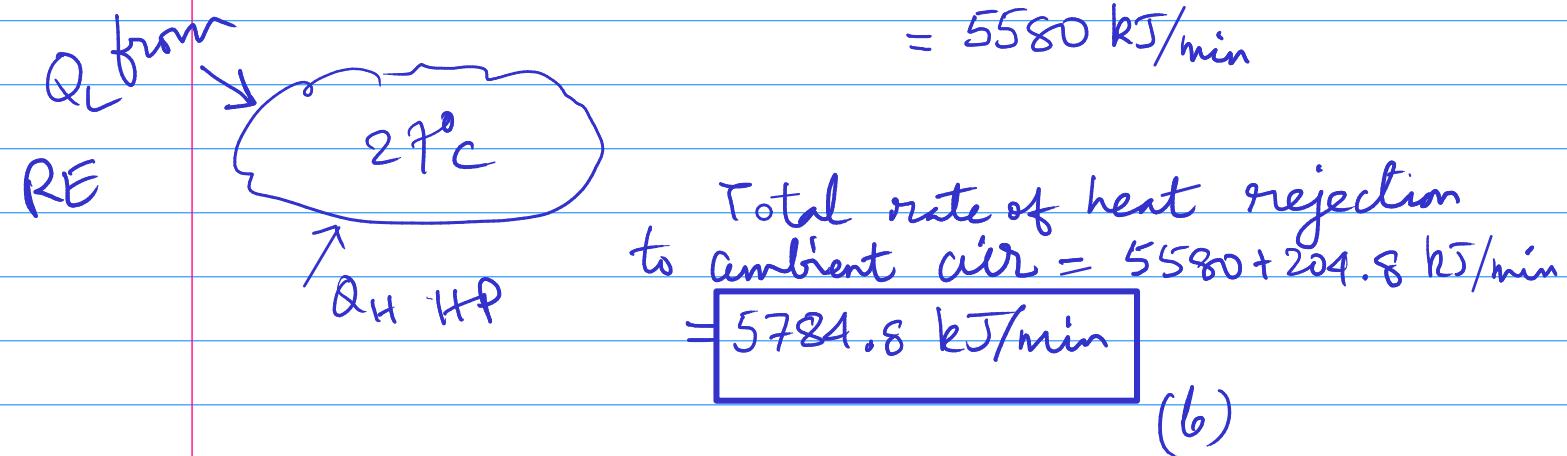
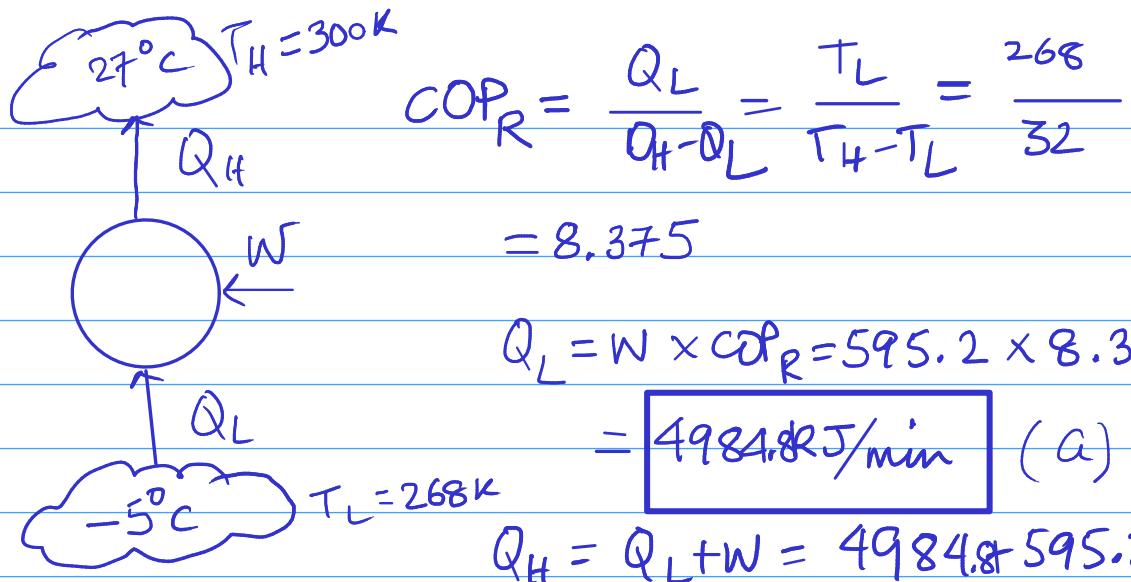
$$\eta_{th,RE} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1173} = 0.744$$

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

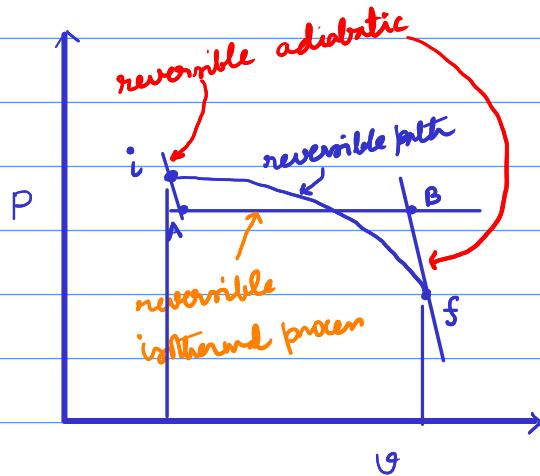
$$Q_L = Q_H - W = 800 - 595.2 = 204.8 \text{ kJ/min}$$

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

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.



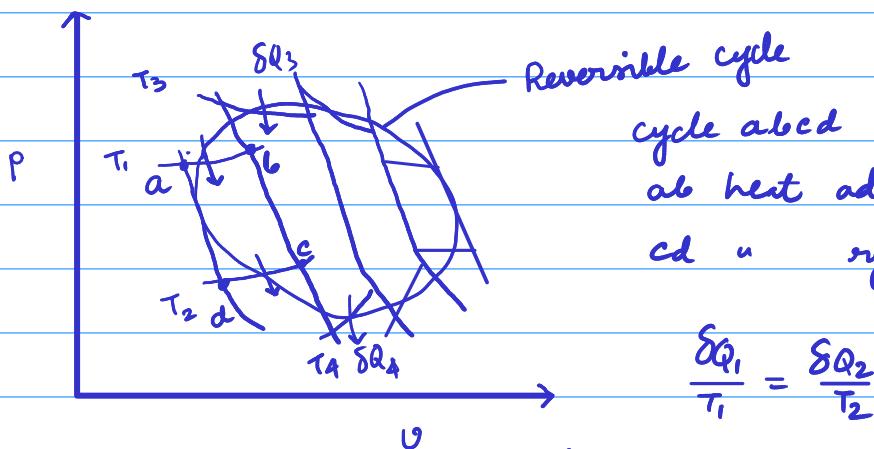
$$Q_{if} - W_{if} = U_f - U_i$$

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

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

$$Q_{if} = Q_{iABf}$$

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.



cycle abcd reversible  
ab heat addition  $\delta Q_1$  at  $T_1$ ,  
cd " rejection  $\delta Q_2$  at  $T_2$

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

If we take the sign convention,

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

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

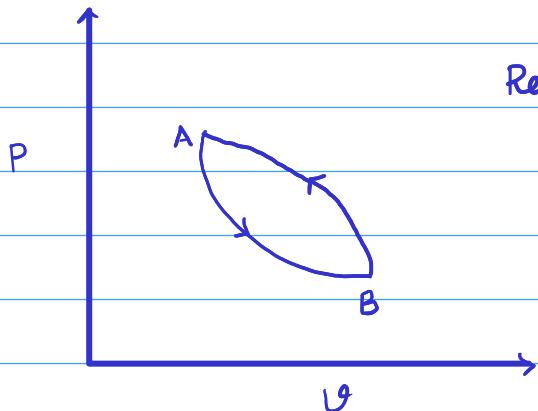
$\oint$

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

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

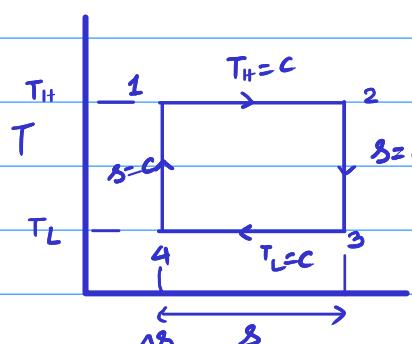
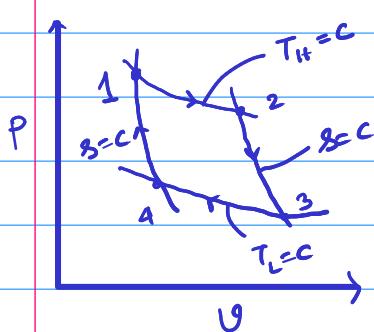
$$S_B - S_A = \frac{1}{T} \int \delta Q = \frac{\Delta Q_B}{T}$$

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

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

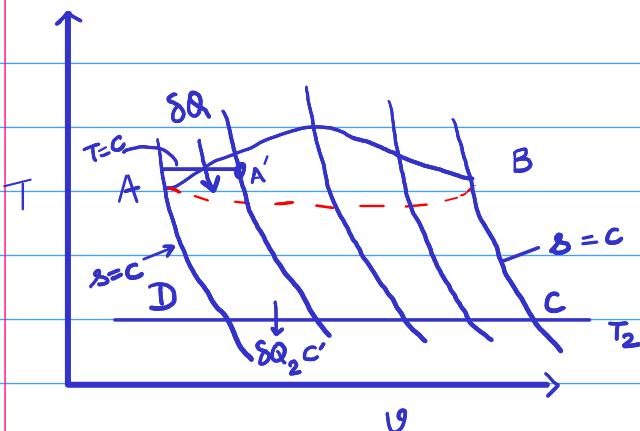
$$dS = 0$$

$S = \text{constant}$



$\Delta S = +ve$  when heat added

$\Delta S = -ve$  u " rejected



AB = reversible path

BA = red dash "

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

$$\eta_{\text{th, rev}} > \eta_{\text{th, irrever}}$$

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

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

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

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

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

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

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

$\frac{\delta Q}{T_2}$  reversible process

$$\begin{aligned} \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}} &> \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{rev}} \\ \left(\frac{\delta Q_2}{\delta Q}\right)_{\text{irrev}} &> \frac{T_2}{T} \end{aligned}$$

$$\delta Q$$

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

$$\delta Q_2$$

$$T_2$$

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

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

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

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

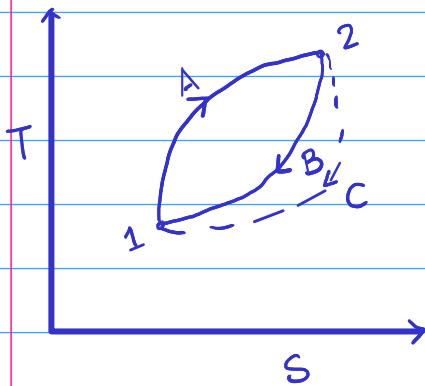
$$\boxed{\oint \frac{\delta Q}{T} \text{ rev} = 0}$$

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

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  $|A2B1|$

$$\oint \frac{\delta Q}{T} = 0 \Rightarrow \int_{A'}^2 \frac{\delta Q}{T} + \int_1^{B_2} \frac{\delta Q}{T} = 0$$

$$\int_1^2 \frac{\delta Q}{T} = - \int_{B_2}^1 \frac{\delta Q}{T}$$

Irreversible cycle  $|A2C1|$

$$\oint \frac{\delta Q}{T} < 0 \Rightarrow \int_{A'}^2 \frac{\delta Q}{T} + \int_{C_2}^1 \frac{\delta Q}{T} < 0$$

$$- \int_{B_2}^1 \frac{\delta Q}{T} + \int_{C_2}^1 \frac{\delta Q}{T} < 0$$

$$\int_{B_2}^1 \frac{\delta Q}{T} > \int_{C_2}^1 \frac{\delta Q}{T}$$

$$\int_{B_2}^1 dS > \int_{C_2}^1 \frac{\delta Q}{T}$$

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

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

$$(S_2 - S_1)_{\text{rev}} > \int_{\text{irrev}}^2 \frac{\delta Q}{T}$$

