MID-II

$E = U + K\cdot E + P\cdot E$

$E_2 - E_1 = (U_2 - U_1) + \frac{1}{2}m(V_2^2 - V_1^2) + mg(h_2 - h_1)$ } Energy eq. for finite changes (or $z_2 - z_1$)

Heat in ⇒ +ive (absorb)(endothermic)

Work done by system ⇒ +ive

Inst. rate $\dot{E}_{cv} = \dot{Q} - \dot{W}$ $= +in - out$ } Energy eq. for control mass/volume

$\Delta U = Q - W$

$U_2 - U_1 + \frac{1}{2}m(v_2^2 - v_1^2) + mg(z_2 - z_1) = {}_1Q_2 - {}_1W_2$

Energy Eq.

$\Delta U + \Delta K\cdot E + \Delta P\cdot E = Q - W$

$Q_{Total} = \int \delta Q$

Spec. heat transfer: $q = \frac{Q}{m}$

I[st] law thermo. $\oint Q = \oint W$

$Q_{net\ in} = W_{net\ out}$

No heat transfer ⇒ Thermal Equilibrium $\Delta Q = 0$

Isobaric ⇒ P: same

Isothermal ⇒ T: same ⇒ Ideal gas law $P_1V_1 = P_2V_2$

Insulated ⇒ $Q = 0$

Adiabatic ⇒ No heat transfer ($Q=0$)

$\Delta U = Q - W = -W$

{ Ideal gas under isothermal Process ⇒ $\Delta U = 0$

$\eta = \frac{W_{net\ out}}{Q_{net\ in}} \times 100\%$

Work done (Ideal gas): $W = nRT\ln\left(\frac{V_2}{V_1}\right)$

$= P_1V_1\ln\left(\frac{V_2}{V_1}\right)$

$\delta W = F dx$

$\delta W = PdV = F\cdot ds$

${}_1W_2 = P(V_2 - V_1)$

$= (P_2 - P_1)(V_2 - V_1)$

$= m(P_2 - P_1)(v_2 - v_1)$

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

Unit: Work ⇒ Joule (J) { Heat ⇒ Joule (J)

Power ⇒ Watt (W)

$\dot{W}$(Power) $= T$ (torque) ω (ang. velocity)

Spec. Work ⇒ $w = \frac{W}{m}$

$P \propto \frac{1}{V}$, $P \propto T$, $V \propto T$

$Pv = RT$

$PV = mRT = n\bar{R}T$

$R = \frac{\bar{R}}{m}$

$n = \frac{m}{M}$

$P\dot{V} = \dot{m}RT = \dot{n}\bar{R}T$

$\dot{V} = \frac{dV}{dt} = \frac{\Delta V}{\Delta t}$

$\frac{y_2 - y_1}{x_2 - x_1}(x - x_1) + y_1 = y$

Steps:-

1. Sketch (mass, heat, work flows; pressure forces)
2. Control Mass/Volume
3. General laws (Energy Eq.)
4. Specific laws
5. Solve using diagrams/table P-v, T-v
6. Formulate

•) Conduction: due to collision of molecules (direct contact)

$\dot{Q} = -kA\frac{dT}{dx}$ } Fourier's Law of Conduction

$\dot{Q}$: rate of heat transfer; k: thermal conductivity; A: Area; $\frac{dT}{dx}$: temperature gradient

k(metals): about $100\ \frac{W}{mK}$

k (insulators): upto $0.01\ \frac{W}{mK}$

•) Convection: due to moving fluid (liquid or gas)

$\dot{Q} = hA\Delta T$ } Newton's Law of Cooling

h: convective heat transfer coeff. $\left(\frac{W}{m^2K}\right)$

1. Natural
2. Forced

•) Radiation: due to electromagnetic waves

$\dot{Q} = \epsilon\sigma AT_s^4$ } Stefan-Boltzman Law

ϵ: emissivity (0 to 1); σ: S-B const ($5.67\times10^{-8}\ W/m^2K^4$); A: surface area; T_s: surface temp. (could be ΔT_s^4)

Spec. internal energy: $u = \frac{U}{m}$ ⇒ $U = um = mu$

$U = U_{liq} + U_{vap}$

$u = u_f + xu_{fg}$

$v = v_f + xv_{fg}$

$x = 0$ ⇒ sat. liq

$x = 1$ ⇒ sat. vap

CL	SV
$P > P_{sat}$	$P < P_{sat}$
$T < T_{sat}$	$T > T_{sat}$
$v < v_f$	$v > v_g$
$h < h_f$	$h > h_g$
$u < u_f$	$u > u_g$
$v \approx v_f$	$v \approx v_g$
$s < s_f$	$s > s_g$

$v_f < v < v_g$

$u_f < u < u_g$

$h_f < h < h_g$

} Two phase (saturated state) $(0 \le x \le 1)$

$m = \frac{V}{v}$

⇒ $m_{liq} = \frac{V_{liq}}{v_f}$

⇒ $m_{vap} = \frac{V_{vap}}{v_g}$

$W_{12} = P(V_2 - V_1)$

$Q_{12} = (U_2 - U_1) + P(V_2 - V_1)$ $\because$ $U = Q - W$, $Q = U + W$

Enthalpy: $H = U + PV$ Unit: $\frac{kJ}{kg}$

$Q_{12} = H_2 - H_1$ (const. pressure)

Spe. Enthalpy $h = u + Pv$ $\rightarrow Q_{12} = m(h_2 - h_1)$

$u = h - Pv$

$h = h_f + x h_{fg}$ $h = \frac{H}{m}$

Eq. of Continuity $\frac{dm_{c.v}}{dt} = \sum \dot{m}_i - \sum \dot{m}_{out}$

if $\frac{dm_{cv}}{dt} = 0$, mass constant

Vol. flow rate $\dot{V} = VA$ (velocity)

Mass. flow rate $\dot{m} = \rho A V = \frac{AV}{v}$

unit kg/s

Energy Eq. for control mass

$E_2 - E_1 = Q_{12} - W_{12}$

or $\frac{dE_{c.m}}{dt} = \dot{Q} - \dot{W}$

Work flow $\dot{W} = FV = P\dot{V} = Pv\dot{m}$

Energy Eq. for control volume

$$\frac{dE_{c.v}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

Steady-State Process

- $\dot{m}_i$ & $\dot{m}_e$: constant
- Prop. of fluid in & out are constant
- Energy within control doesn't accumulate over time
- Control volume: stationary
- $\frac{dm_{cv}}{dt} = 0$, $\frac{dE_{c.v}}{dt} = 0$
- Rate of heat & Work: constant

Continuity Eq. $\sum \dot{m}_i = \sum \dot{m}_e$

Energy Eq. $\dot{Q}_{cv} + \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \sum \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right) + \dot{W}_{cv}$ — For multiple flow streams

power unit $\left(\frac{J}{s}\right)$: watt (W)

Continuity Eq. $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy Eq. $\dot{Q}_{cv} + \dot{m}\left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{m}\left(h_e + \frac{V_e^2}{2} + gz_e\right) + \dot{W}_{cv}$ — For single flow stream

$$q + h_i + \frac{V_i^2}{2} + gz_i = h_e + \frac{V_e^2}{2} + gz_e + w$$

$q = \frac{\dot{Q}_{cv}}{\dot{m}}$ Unit: kJ/kg — heat transfer per unit mass

$w = \frac{\dot{W}_{c.v}}{\dot{m}}$ Unit: kJ/kg — work per unit mass

Heat Exchanger: $Q = 0$, $K.E = 0$, $P.E = 0$, $W = 0$ — $\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$

Nozzle: $Q = 0$, $W = 0$, $P.E_i \approx P.E_e$, $\dot{m}$ = constant

Diffuser: Same as nozzle, but in opposite direction.

$K.E_i \uparrow$ $K.E_e \downarrow$ $h_i + \frac{V_i^2}{2} = h_e + \frac{V_e^2}{2}$

Throttle: $K.E \approx 0$, $P.E = 0$, $W = 0$, $Q = 0$

$h_i = h_e$

Turbines: $P.E = 0$, $K.E_i = 0$, $Q = 0$, $K.E_e = 0$

Compressor/Pump: $P.E = 0$, $K.E_i = 0$, $K.E_e = 0$, $Q = 0$

MID-I

Total Energy = K.E + P.E + U $= \frac{1}{2}mv^2 + mgh + U$

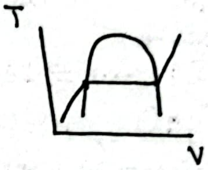
$\Delta U = Q - W$

$\Rightarrow W \rightarrow$ -ive: On system

$\Rightarrow W \rightarrow$ +ive: by system

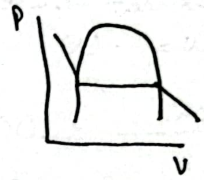
$\Rightarrow q \rightarrow$ -ive: release (exo)

$\Rightarrow q \rightarrow$ +ive: absorb (endo)



Sp. Volume: $v = \frac{V}{m}$

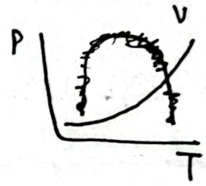
Sp. Density: $\frac{m}{V} = \frac{1}{v} \Rightarrow \rho = \frac{m}{V}$



$P \propto \frac{1}{V}$ $P \propto T$ $V \propto T$

$v_{fg} = v_g - v_f$

$v = v_f + x v_{fg}$



$V_{Total} = V_{liq} + V_{vap} = m_{liq} v_f + m_{vap} v_g$

$x = \frac{m_{vap}}{M}$

$v_f < v < v_g$

$\Rightarrow$ Two-phase

Ideal gas law holds

$\Rightarrow$ low press.

$\Rightarrow$ high temp

$\Rightarrow$ low density

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

$\Rightarrow PV = ZRT$ — $Z = 1$: ideal gas; $Z \neq 1$: non ideal gas

$Z < 1$: attractive force; $Z > 1$: repulsive force

$P_r = \frac{P}{P_c}$ $T_r = \frac{T}{T_c}$

$T >> T_c$, $P << P_c$ — nearly ideal gas

$P \rightarrow P_c$: non-ideal gas

POST MID-II

$$\eta_{thermal} = \frac{W}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

released (Q_L), absorbed (Q_H)

Efficiency of real engine: $W = Q_H - Q_L$

COP: $\beta = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}$ (refrigerator)

COP: $\beta' = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L}$ (heat pump)

2^{nd} Law KP: $\eta_{thermal} < 100\%$

2^{nd} Law C: $\beta < \infty$ → Inequality of Clausius $\oint \frac{\delta Q}{T} \le 0$

Carnot Cycle

1. Reversible Isothermal expansion (Q & $W \Rightarrow$ +ive)
2. " Adiabatic expansion ($Q=0$, $W \Rightarrow$ -ive) ($Q_H = T_H \Delta S$)
3. " Isothermal compression ($W \Rightarrow$ -ive)
4. " Adiabatic " ($Q=0$, $W \Rightarrow$ -ive) ($Q_L = T_L \Delta S$)

~~① Isothermal expansion~~

$$\eta_{carnot} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

Propositions: ① $\eta_{any} \le \eta_{reversible}$

② $\eta_{rev1} = \eta_{rev2}$

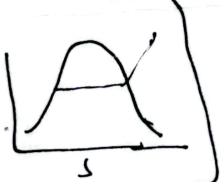
Entropy $dS = \frac{\delta Q}{T}\Big|_{rev}$ $\quad \oint \delta Q = Q_H - Q_L$

Entropy Change $S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\Big|_{rev}$

Rev. Heat Engine: $\oint \delta Q \ge 0$, $\oint \frac{\delta Q}{T} \ge 0$ $\left(\oint \frac{\delta Q}{T} = 0\right)$

Irr. Heat Engine $\oint \delta Q \ge 0$ $\oint \frac{\delta Q}{T} < 0$

Rev. Refrigerator: $\oint \delta Q \le 0$ $\{ \oint \frac{\delta Q}{T} = 0$



Irrev. Refrigeration: $\oint \delta Q < 0$ $\{ \oint \frac{\delta Q}{T} < 0$

$s = (1-x) s_{f} + x s_g$ $\quad$ Spec entropy $s = \frac{S}{m} \left(\frac{kJ}{kg K}\right)$

$s = s_f + x s_{fg}$

Entropy in Rev. process: (Carnot Cycle)

① $S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\Big|_{rev} = \frac{{}_1Q_2}{T_H}$

② $dS = \frac{\delta Q}{T}\Big|_{rev} = 0$ (isentropic) → const. entropy

③ $S_4 - S_3 = \int_3^4 \frac{\delta Q}{T}\Big|_{rev} = \frac{-{}_3Q_4}{T_L}$

④ $dS = \frac{\delta Q}{T}\Big|_{rev} = 0$ (isentropic)

$$\eta_{Ther} = \frac{W_{net}}{Q_H} = \frac{\text{area } 1-2-3-4-1}{\text{area } 1-2-b-a-1}$$

$$S_2 - S_1 = \frac{{}_1q_2}{T} = \frac{h_{fg}}{T}$$

rev. adiabatic $\Delta q = 0$

Entropy of Solid/Liquid: $ds \simeq \frac{du}{T} \simeq \frac{C}{T} dT$ $\{ s_2 - s_1 \simeq C \ln \frac{T_2}{T_1}$

Rankine Cycle

① (1-2): rev. adiabatic (addition) pumping process in ~~boiler~~ pump $\{ \Delta S = 0,\ Q = 0,\ S \Rightarrow$ const. $\}$ Isentropic

② (2-3): Const. pressure transfer of heat in boiler $\}$ $P \Rightarrow$ const, Isobaric
$\Rightarrow$ Comp. liq into vapor

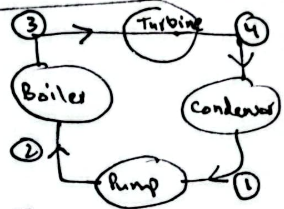
③ (3-4): Rev. adiabatic expansion in turbine $\}$ $\Delta S = 0$, $Q = 0$, $S \Rightarrow$ Const, Isentropic
$\Rightarrow$ Superheated vapor expand isentropically producing work

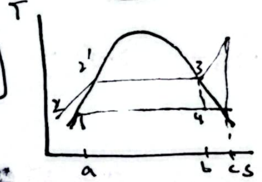
④ (4-1): Const. pressure transfer of heat in condensor (heat rejection) $\}$ $P \Rightarrow$ const, Isobaric
$\Rightarrow$ back to liquid (state 1)

$$\eta_{th} = \frac{W_{net}}{q_H} = \frac{\text{area } 1-2-2'-3-4-1}{\text{area } a-2-2'-3-b-a}$$

K.E $\simeq 0$, P.E $\simeq 0$ $\quad = \frac{q_H - q_L}{q_H}$

$\eta_{Rankine} < \eta_{carnot}$





Efficiency of Rankine Cycle:

① Lowering condensor pressure (P_4)
$\Rightarrow$ also increases turbine moisture content

② Superheating steam (boiler) (T_3)

③ Increasing boiler pressure (P_2)