



Exam 1



Micro vs. Macroscale

Thought Exercise

- Refrigerator is closed, insulated room
• Fridge Turned on at t=0



1) Closed Fridge up same down
a) Fridge Temperature? ↑ - ↓ Inside cools

b) Room Temperature? ↑ - ↓ Room warms
Room heats due to cooling process

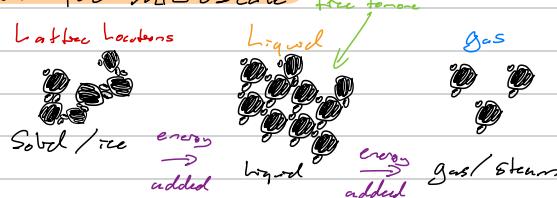
2) Open Fridge

a) Average Room Temp? ↑ - ↓ No Fridge, room room
energy needed to

Two perspectives on energy

- intuition
1) Microscale: Behavior of atoms, molecules, electrons, etc.
2) Macroscale: Pumps, turbines, power plants, etc.

At the microscale



Takeaway

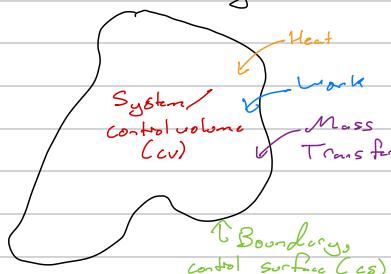
Structure @ Macroscale
dictates Macro state
of energy

→ Modes of energy storage @ the microscale

- 1) Translational Motion (KE)
 - 2) Vibrational Energy
 - 3) Rotational Motion
 - 4) Electron Translation
 - 5) Phase Changes
 - 6) Chemical Bonds
 - 7) Nuclear Bonds
- 1-4: Sensible modes. Related to activity/motion. Related closely to temperature
- Sum up \rightarrow Changes to internal energy
- U or u
- | | |
|---------|----------------|
| Capital | U |
| Total | u |
| Basis | kJ/kg |
- 5-7: Latent modes. Tend to structural changes

→ Modeling Energy @ the macroscale

Define a system:

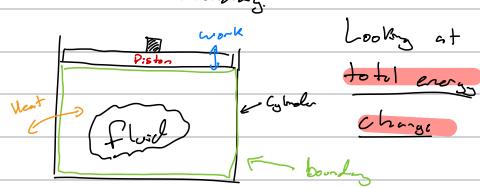


Energy can cross boundary in 3 ways:

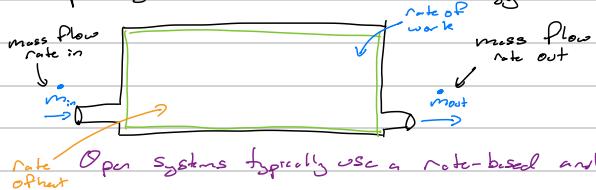
- 1) Heat
- 2) Work
- 3) Mass Transfer

Open vs. Closed Systems

Closed System: No mass transfer across boundary.



Open System: All forms of energy transfer are possible



$$\dot{m} = \rho V_{avg} A_C$$

Mass flow rate (\dot{m}):
 \dot{m} = density ρ \times average velocity V_{avg} \times cross-section area A_C

Application: Wind Turbine



If we opened up the system to the ground it would make a big difference bc the unaffected wind cancels itself out

First Law of Thermodynamics

→ **Conservation of Energy:** Energy cannot be created nor destroyed

→ Can also write total energy as a mass-specific basis:

$$\frac{E}{m} = e = u + \frac{1}{2} m v^2 + g z$$

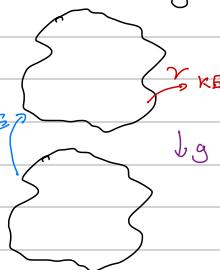
↓ KE ↓ PE ↓ elevation

- 1) Energy stored within a system
- 2) Energy transfer across the boundary

① Stored Energy

$$E = PE + KE + U$$

↓ KE ↓ PE ↓ Internal Energy (IE)



② Energy crossing Boundary

- a) Heat Transfer (Q) - energy transfer due to a temperature difference
- b) Work (w) - rate of heat transfer $\dot{w} = \frac{Q}{\Delta t}$

Modes of Heat Transfer

- 1) **Conduction:** energy transfer from higher to lower energetic matter due to direct interaction
- 2) **Convection:** enhanced conduction due to fluid motion
- 3) **Radiation:** energy transfer via electromagnetic waves
 ↗ Physics definition: $w = Fd$; force acting over a distance

Work (w): energy transfer w/o a temperature difference

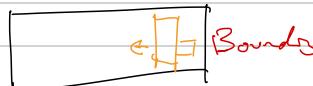
w : Total work over some time Σw

\dot{w} : Rate of work \dot{w} (Watts)

→ Different Types of Work

1) Mechanical Work:

- a) Moving Boundary - piston
- b) Shaft work



2) Electrical Work:

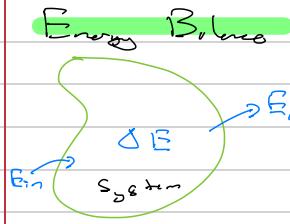


Mass Flow Energy

$E_{mass} = \text{Total Energy}$, transferred due to mass transfer over some time Σw

E_{mass} : rate Basis Σw

First Law of Thermodynamics



$$E_{in} - E_{out} = \Delta E \quad \text{Heat + work}$$

$$\cdot E_{in} = Q_{in} + W_{in} + E_{mass,in}$$

$$\cdot E_{out} = Q_{out} + W_{out} + E_{mass,out}$$

$$\cdot \Delta E = E_{final} - E_{initial}$$

$$\hookrightarrow \Delta E = (U_2 - U_1) + \frac{1}{2}(V_2^2 - V_1^2) + g(z_2 - z_1)$$

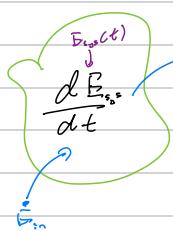
Starting point for Law on total Basis

This is an altered derivation of stored Energy formula

Combining Equations for unitary Law

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = (U_2 - U_1) + \frac{1}{2}(m_2 V_2^2 - m_1 V_1^2) + g(m_2 z_2 - m_1 z_1)$$

→ On a Rate Basis



$$E_{in} - E_{out} = \frac{dE}{dt}$$

Starting point for Law on total Basis

Pure Substances

Properties of Pure Substances

- No mixtures (except air)

Goal: Calculate some properties given others

→ Given the thermodynamic state of a substance

→ Specify two independent state variables

Three primary types of substances

1) Ideal Gases (or close to/really)

- Blastic Collisions
- No Intermolecular Forces
- Simple, Low density gases

Approach: Use equations

2) True Liquids (Incompressible Liquids)

→ No Phase change

Approach: Use (different) equations

3) Phase Change Fluids (Sticky things)

Approach: Use tables + Props

→ or software

Examples of Ideal Gases

- air
- N_2

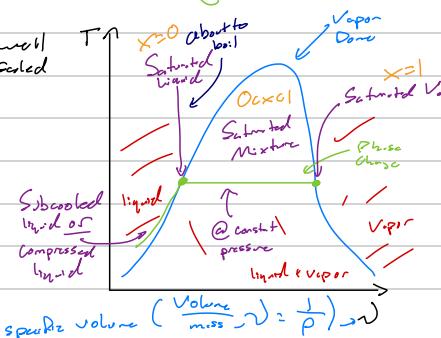
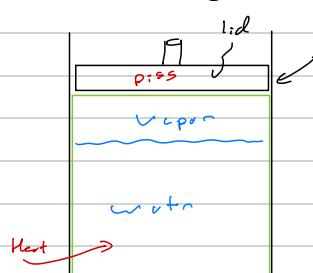
Examples of True Liquids

- water
- oil

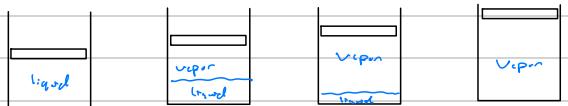
Examples of Phase Change Liquids

- water/steam
- refrigerants

Phase Change Process Boiling @ constant pressure



• Phase change quantified by the quality: $X = \frac{m_{\text{vapor}}}{m_{\text{total}}} = \frac{m_{\text{vapor}}}{m_{\text{vapor}} + m_{\text{liquid}}}$



Regions

1) Compressed Liquid Region

At a given pressure: $T < T_{sat}$

At a given temperature: $P > P_{sat}$ \leftarrow compressed liquid

2) Saturated Liquid

$$\text{Ques} \rightarrow X = 0, T = T_{sat} \neq P = P_{sat}$$

3) Saturated mixture

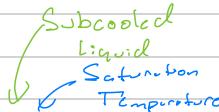
$$0 < X < 1, T = T_{sat} \neq P = P_{sat}$$

4) Saturated Vapor

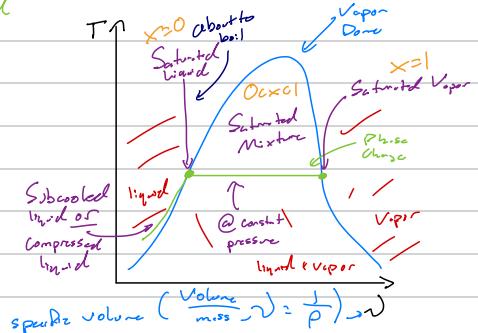
$$X = 1, T = T_{sat} \neq P = P_{sat}$$

5) Superheated vapor

$$T > T_{sat}, P < P_{sat}$$



Revolving



Working with Steam Tables

a) Saturated water (mixture)

(i) Table A4 (by temperature)

(ii) Table A5 (by Pressure)

b) Superheated vapor \rightarrow Table A6

c) Compressed liquid \rightarrow Table A7

Steps for Property Lookup

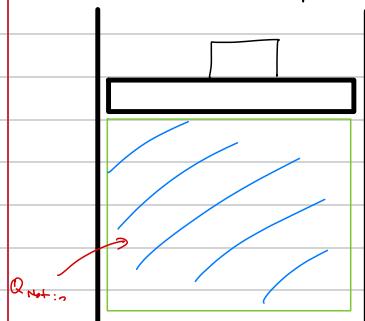
- 1) Start with Saturated mixture table
- 2) Identify the phase (mixture, vapor, or liquid)
- 3) Go to appropriate table

Example: Given water @ 90°C , 50 kPa \rightarrow Determine phase Outlined in Textbook

$$E_{meas} = m_e e_{meas} = m_e \left(\frac{P}{P_0} + \frac{V^2}{2} + gz \right)$$

Closed Systems

- Consider a piston-cylinder system



1st Law

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = U_2 - U_1 \quad \text{or } \sum KJ \quad \text{or } \sum \frac{KJ}{kg}$$

System Mass $\rightarrow m(U_2 - U_1)$

Mass specific internal energy $\rightarrow \frac{\sum KJ}{\sum kg}$

$$Q_{net,in} - W_{net,out}$$

$$\Rightarrow Q_{net,in} - W_{net,out} = m(U_2 - U_1)$$

Q_{in} : Heat transfer into the system

W_{in} : Work done on the system

Q_{out} : Heat transfer out of the system

W_{out} : Work done by the system

Calculating boundary work



①
②

$$dW = F_{ext} ds$$

$$= P(A_{ext}) ds$$

Pressure: $\frac{Force}{Area}$, area \rightarrow force

A is the cross-sectional area of the piston



Integrate between ① to ②

$$W_{piston} = \int_1^2 P dV = W_{out}$$

Positive when volume increases

Done by the system

• If pressure is constant (isobaric process)

$$\rightarrow W_{piston} = P \int_1^2 dV = P(V_2 - V_1) = P\Delta V$$

Writing 1st law is
most common place to start

• Find Heat Added from ① \rightarrow ②

$$1^{\text{st}} \text{ Law: } (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m(U_2 - U_1)$$

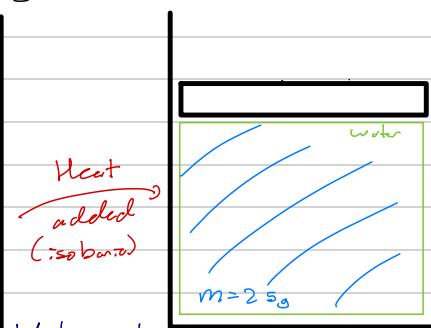
Heat added only

$$\text{Work: } W_{piston} = P(V_2 - V_1) = P_m(V_2 - V_1)$$

Specific volume

① Go to sat vapor table @ 300 kPa
Sat $V_{\text{apor}}(V_1) = 0.60582 \frac{m^3}{kg}$
Sat $V_{\text{apor}}(U_1) = 2543.2 \frac{kg}{m^3}$
Sat Temp = 133°; 200 > 133 ∴ Superheated

Example: Closed System



①

②

$$P_1 = 300 \text{ kPa}$$

$$T_2 = 200^\circ C, P_2 = P_1 = 300 \text{ kPa}$$

Saturated vapor \Leftrightarrow Treat as phase change fluid

$$\text{Calculation: } W_{piston} = P_m(V_2 - V_1) = 0.83 \text{ kJ}$$

$$Q_{in} = m(U_2 - U_1) + w_{out} = 3.5 \text{ kJ}$$

Positive is
 w_{out}

↓

$$V_2 = 0.716 \frac{m^3}{kg}$$

$$U_2 = 2681.0 \frac{kJ}{kg}$$

② Go to superheated table @ 0.3 mPa

Polytropic Processes

Boundary work for a polytropic process

$$\rightarrow \text{Polytropic process: } PV^n = \text{Constant} = C \Rightarrow P = CV^{-n}$$

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

• Some Examples

<u>n</u>	<u>constant</u>
0	pressure \rightarrow isobaric
1	temperature \rightarrow isothermal
$\gamma = \frac{C_p}{C_v}$	entropy \rightarrow isentropic
$\rightarrow \infty$	volume \rightarrow isochoric

Gamma = ratio of specific heats

Example: Piston-Cylinder with Nitrogen Entertations: deg's



Want to use $\frac{P_2 V_2 - P_1 V_1}{1-n}$

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

$$V_2^n = \frac{P_1 V_1^n}{P_2}$$

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

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

$$V_2 = e^{\left(\frac{1}{n} \cdot \ln\left(\frac{P_1 V_1^n}{P_2}\right)\right)} = 0.08636 \text{ m}^3$$

Back to Work

$$\begin{aligned} W_{\text{poly}} &= \int_{V_1}^{V_2} P \, dV \\ &= \int_{V_1}^{V_2} C V^{-n} \, dV \\ &= C \left[\frac{1}{1-n} V^{1-n} \right]_{V_1}^{V_2} \\ &= C \left(\frac{V_2^{1-n} - V_1^{1-n}}{1-n} \right) \\ &= C \left(\frac{\frac{P_2}{C} \cdot V_2 - \frac{P_1}{C} \cdot V_1}{1-n} \right) \\ \Rightarrow W_{\text{poly}} &= \frac{P_2 V_2 - P_1 V_1}{1-n} \end{aligned}$$

$$\begin{aligned} V_1 &= 0.07 \text{ m}^3 & V_2 &=? \\ P_1 &= 130 \text{ kPa} & P_2 &= 100 \text{ kPa} \\ T_1 &= 120^\circ \text{C} & T_2 &= 100^\circ \text{C} \end{aligned}$$

Find work done by Process

Ideal Gas Law / Eq of State

$$PV = nRT$$

↓
Universal Gas Constant

$$\text{For ECHE225: } PV = mRT$$

↳ Spec. Rho to a particular gas

$$\rightarrow P = \rho RT \text{ or } \rho = \frac{P}{RT}$$

$$PV = mRT$$

$$mR = \frac{PV}{T}$$

C
mass

$$\rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$V_2 = \frac{T_2 P_1 V_1}{P_2 T_1} = 0.0866 \text{ m}^3$$

Positive Number so this is work out

Finding Δu

3.) Phase change fluids

a) For a saturated mixture

$$u = X_u g + (1-X) u_f$$

available sat vapor value sat liquid value

or

$$u = u_f + X(u_g - u_f)$$

or

$$v = v_f + X(v_g - v_f)$$

or

$$s = s_f + X(s_g - s_f)$$

b) For compressed liquids

u, v much stronger functions of temperature than pressure

Short cut / Estimate: Bulk vs compressed liquid properties at the saturation point

$$u_{cl} = u_f(T)$$

↑
comp. h.
↑
sat liquid &
temp h. T

vs. (saturated liquid) based on temperature.

↳ It is incorrect to say $u_{cl} = u_f(T)$

1) Ideal Gases

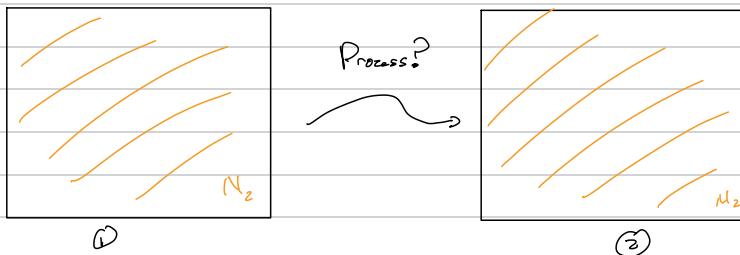
- (1 point)
- Internal energy is only a function of temperature
 - Use specific heat value - energy required to increase temperature by 1K (per unit mass) $\sum \frac{C_V}{k_B \cdot K}$
 - Two types:
 - C_V : Specific heat at constant volume
 - directly relates to changes in internal energy
 - what we need for closed systems
 - $C_V = \frac{du}{dT} \rightarrow du = C_V(T) dT$
 - $\Delta u = u_2 - u_1 = \int_1^2 C_V(T) dT$
 - C_V is typically constant: $u_2 - u_1 = C_V, \text{Avg} (T_2 - T_1)$
 - C_p : Specific heat at constant pressure
 - directly relates to enthalpy
 - open systems will discuss later

2) True Liquids/Solids

$\hookrightarrow C_V = C_p = C$

$$\left(\begin{array}{l} \Delta u = u_2 - u_1 = \int_1^2 C(T) dT = C_{\text{Avg}} (T_2 - T_1) \quad \text{definition} \\ \Delta u = C \Delta T \quad \text{mass specific} \\ \Delta u = mc \Delta T \quad \text{total basis} \end{array} \right)$$

Example: Rigid Tank filled with N_2



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

$$T_1 = 25^\circ\text{C} = 298.15 \text{ K}$$

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

Rigid Tank = Constant volume
Treat N_2 as an ideal gas
Process unknown

Steps

- Write 1st law and simplify
- Set eqn 1 to ideal gas
- Determine T_2 with $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
- Collect constants and solve

Since it's ideal

$$1^{\text{st}} \text{ Law: } (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m(u_2 - u_1) = m C_V (T_2 - T_1)$$

ideal G.s E.S: $PV = mRT \leftarrow T \text{ must be in Kelvin to work correctly}$

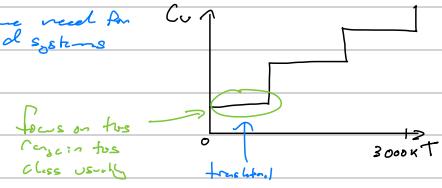
$$V_1 = V_2 \quad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \rightarrow T_2 = \frac{T_1 P_2}{P_1} = 3T_1 = 894 \text{ K}$$

Table lookup

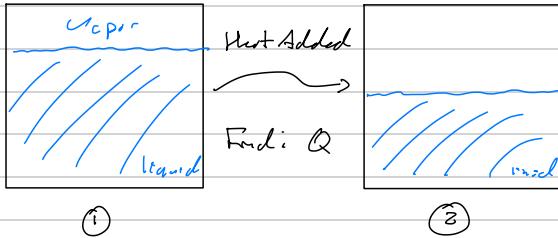
$T \text{ (K)}$	$C_V \left(\frac{u_0}{K_B \cdot K} \right)$
$298 \approx 300$	0.743
$894 \approx 900$	0.849

$$\left. \begin{aligned} & \left. \begin{aligned} & C_{V, \text{Avg}} = \frac{0.743 + 0.849}{2} = \end{aligned} \right. \\ & \left. \begin{aligned} & Q_{in} = m C_V \Delta T \Rightarrow q_{in} = \frac{Q_{in}}{m} \rightarrow 475 \text{ kJ/kg} \end{aligned} \right. \end{aligned} \right\}$$

$$Q_{in} = m C_V \Delta T \Rightarrow q_{in} = \frac{Q_{in}}{m} \rightarrow 475 \text{ kJ/kg}$$



Example S-30: 10L water in a rigid tank



$$T_1 = 100^\circ\text{C}$$

$$x_1 = 0.123$$

$$T_2 = 150^\circ\text{C}$$

$$v_2 = v_1 = 0.207 \frac{\text{m}^3}{\text{kg}}$$

$$\text{1st Law: } (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m(u_2 - u_1)$$

$$v_1 = x_1 v_g + (1-x_1) v_f = 0.207 \frac{\text{m}^3}{\text{kg}}$$

$$u_1 = x_1 u_{g,1} + (1-x_1) u_{f,1} = 678.8 \frac{\text{kJ}}{\text{kg}}$$

plus

$$\therefore T_2 = 150^\circ\text{C} \quad \left. \begin{array}{l} \text{Go to temperature table @ } 150^\circ\text{C} \\ \text{if } v < v_f \rightarrow \text{compressed liquid} \end{array} \right\}$$

$$v_2 = 0.207 \frac{\text{m}^3}{\text{kg}} \quad \left. \begin{array}{l} \text{if } v > v_g \rightarrow \text{superheated vapor} \\ \text{if } v_f < v < v_g \rightarrow \text{saturated mixture} \end{array} \right.$$

$$v_2 = 0.207 \frac{\text{m}^3}{\text{kg}}$$

$$\text{Back to 1st Law: } Q_{in} = m(u_2 - u_1) \quad \text{10L} \rightarrow m^3 = 0.01$$

$$\cdot \text{Find mass? } m = \rho V = \frac{V}{v} = \frac{0.01}{0.207} = 0.048 \text{ kg}$$

$$\therefore Q_{in} = 0.048(u_2 - u_1) = \boxed{1643.6 \text{ kJ}}$$

$$j = \frac{V}{m} \quad P = \frac{m}{V}$$

$$V = m j$$

Volume remains the same $\left. \begin{array}{l} \{ \\ v_2 = v_1 = v \end{array} \right\}$
Mass remains the same

From Sat Water Table @ 150°C

$$\begin{aligned} v_1 &= 1.622 \frac{\text{m}^3}{\text{kg}} & v_{f,1} &= 0.00104 \frac{\text{m}^3}{\text{kg}} \\ u_{g,1} &= 2506 \frac{\text{kJ}}{\text{kg}} & u_{f,1} &= 419.06 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

From Sat Water Table @ 150°C

$$\begin{aligned} v_{f,2} &= 0.001091 \frac{\text{m}^3}{\text{kg}} & v_{g,2} &= 0.3924 \frac{\text{m}^3}{\text{kg}} \\ u_{f,2} &= 631.66 \frac{\text{kJ}}{\text{kg}} & u_{g,2} &= 2559.1 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

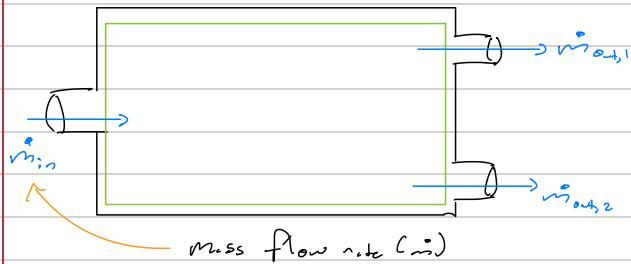
$$v_2 = v_{f,2} + x_2(v_{g,2} - v_{f,2}) = 0.207 \frac{\text{m}^3}{\text{kg}}$$

$$x_2 = \frac{0.207 - v_{f,2}}{v_{g,2} - v_{f,2}} = 0.525$$

Find mixture internal energy value

$$u_2 = u_{g,2} x_2 + (1-x_2) u_{f,2} = 1643.6 \frac{\text{kJ}}{\text{kg}}$$

Open Systems



- mass crossing in area per unit time

density ρ avg velocity V_{avg} cross sectional area

- Simple Expression: $\dot{m} = \rho V_{avg} A_c$



- No velocity @ tube wall
- Max. velocity at center of pipe

velocity profile

- Locally: $\dot{m} = \int_{A_c} \rho v_n dA_c$

- Equate \dot{m} expressions
Flow: incompressible

$$\rho V_{avg} A_c = \int_{A_c} \rho V_n dA_c$$

$$= \rho \int_{A_c} V_n dA_c$$

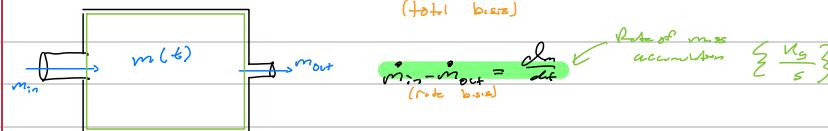
Volumetric Flow Rate

$$\dot{V} = \frac{\dot{m}}{\rho} = V_{avg} A_c \quad (\text{in } \frac{\text{m}^3}{\text{s}})$$

$$\Rightarrow V_{avg} = \frac{1}{A_c} \int V_n dA_c$$

Conservation Laws

1) Mass

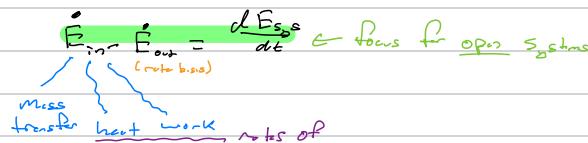


$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm}{dt} \quad \left\{ \begin{array}{l} \text{Rate of mass accumulation} \\ \text{in kg/s} \end{array} \right\}$$

Extend to multiple inlets/outlets: $\sum_i \dot{m}_{in,i} - \sum_j \dot{m}_{out,j} = \frac{dm}{dt}$

2) Energy (1st Law Thermodynamics)

$$E_{in} - E_{out} = \Delta E_{sys} \quad \left(\text{Total basis} \right)$$



Will focus on steady flow analysis $\Rightarrow \frac{d}{dt} = 0$, in and out balance P & En laws
↳ steady flow devices

\Rightarrow No accumulation of mass or energy inside our system

• For Steady Equations

- Mass: $\dot{m}_{in} = \dot{m}_{out}$ (for flow sense)
- Energy: $E_{in} = E_{out}$

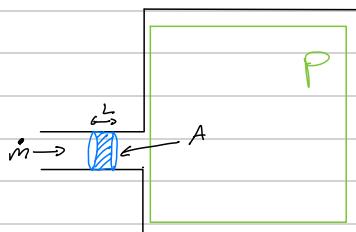
Corresponds to steady, normal operations

1st Law for Steady Open Systems

$$(\dot{Q}_{in} - \dot{Q}_{out}) + (\dot{W}_{in} - \dot{W}_{out}) + (\dot{E}_{mass,in} - \dot{E}_{mass,out}) = 0$$

net rate heat transfer
 net rate work transfer
 net rate mass transfer

Flow Work Energy



$$\begin{aligned} W_{Flow} &= PL \\ &= PA\bar{L} \quad \leftarrow \text{Flow Fluid is with zero force} \\ &= PV \end{aligned}$$

- \dot{E}_{mass} elements
 - (i) Kinetic Energy $\left(\frac{1}{2}V_{avg}^2\right)$
 - (ii) Internal Energy (U)
 - (iii) Potential Energy (gz)
 - (iv) Flow Work Energy (PV)

$$\frac{W_{Flow}}{m} = m_{Flow} = \frac{PV}{m} = P$$

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

Energy Terms Brought together

$$\dot{E}_{mass} = m \underbrace{(U + PV)}_{\text{enthalpy } (h)} + \frac{1}{2} V_{avg}^2 + gz$$

- Introduce the enthalpy $h = U + PV$:
 $h = U + PV$ (also total $H = U + PV$)
- $\Rightarrow \dot{E}_{mass} = m (h + \frac{1}{2} V_{avg}^2 + gz)$

Conservation of Energy (single inlet, single outlet)

$$(\dot{Q}_{in} - \dot{Q}_{out}) + (\dot{W}_{in} - \dot{W}_{out}) + m [(h_{in} - h_{out}) + \frac{1}{2} (V_{in}^2 - V_{out}^2) + g(z_{in} - z_{out})] = 0$$

- (i) Move Flow Energy to RHS, define
- (ii) Let $out = 2, in = 1$

$$\Rightarrow \dot{Q}_{out} + \dot{W}_{out} = m [h_2 - h_1 + \frac{1}{2} (V_2^2 - V_1^2) + g(z_2 - z_1)]$$

Enthalpy Calculating Δh @ constant pressure

$$\text{D) Ideal Gas: } C_p = \frac{dh}{dT} \Big|_P$$

$$\Rightarrow \Delta h = \int_1^2 C_p dT$$

2) True Liquids: $C_p = C_v = C$

$$\Delta h = C_{avg} \Delta T$$

3) Phase Change Fluids

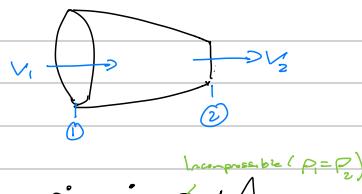
- Tables with missing values

$$\begin{aligned} h &= h_f + x(h_g - h_f) \quad \text{Interpolation} \\ h &= xh_g + (1-x)h_f \end{aligned}$$

Steady Flow Devices

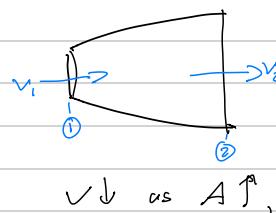
1) Nozzles / Diffusers

Nozzle



$$\text{mass: } \dot{m}_1 = \rho_1 V_1 A_1 \\ = P_2 V_2 A_2 = \dot{m}_2 \\ \Rightarrow V_2 \uparrow \text{ as } A \downarrow, P_2 < P_1$$

Diffuser

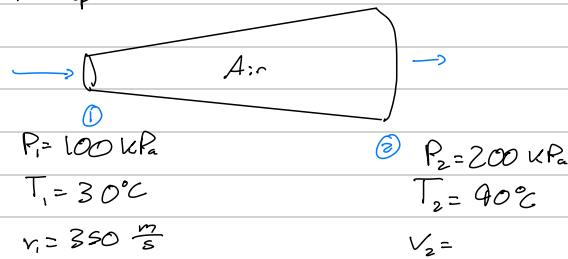


$$\text{Energy Analysis: } Q_{\text{heat}} + W_{\text{work}} = \dot{m} [h_2 - h_1 + \frac{1}{2}(V_2^2 - V_1^2) + g(z_2 - z_1)]$$

Assumptions: $\Delta PE \approx 0$ ($z_2 \approx z_1$)
 $\dot{Q}_{\text{heat}} = 0$ (adiabatic)
 $W_{\text{work}} \approx 0$ (positive system)

$\rightarrow E_{\text{exchanges}} \text{ enthalpy for kinetic Energy}$

Example 6-26



Find: V_2 , something about the areas?

$$\Rightarrow V_2 = \sqrt{V_1^2 - 2c_p \Delta T} \quad c_p = 1.007 \frac{\text{kJ}}{\text{kgK}}$$

$\left(\frac{\text{m}^2}{\text{s}^2} \right) \times 1000 \quad \left\{ \frac{\text{KJ}}{\text{K}} \right\}$

$$h_{2,1} = \dot{m} \left[(h_2 - h_1) + \frac{1}{2}(V_2^2 - V_1^2) \right]$$

$$Z(h_2 - h_1) = \dot{m} \left(\frac{1}{2} (V_2^2 - V_1^2) \right)$$

$$Z(h_2 - h_1) = V_2^2 - V_1^2$$

$$V_2 = \sqrt{V_1^2 - Z(h_2 - h_1)} \quad \text{Need to calculate } \Delta h$$

$$\text{Ideal gas: } \Delta h = c_p A_v \Delta T$$

$$\left(\frac{\text{m}^2}{\text{s}^2} \right) = \frac{\text{J}}{\text{kg}}$$

$$\text{mass: } \dot{m}_1 = \dot{m}_2 \\ P_1 V_1 A_1 = P_2 V_2 A_2 \rightarrow \frac{A_2}{A_1} = \frac{P_1 V_1}{P_2 V_2} \quad \text{If } P \text{ is constant} \rightarrow \frac{A_2}{A_1} = \frac{V_1}{V_2} = 6.6$$

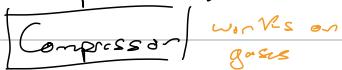
$$\rightarrow \text{Use ideal gas Eq: } P = \frac{P}{RT}, P_1 = \frac{P}{RT_1} \text{ and } P_2 = \frac{P}{RT_2}$$

Don't make bad assumptions

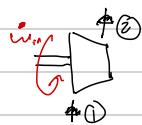
$$\frac{P_1 V_1}{P_2 V_2} = \frac{V_1}{V_2} \left(\frac{P_1 R T_2}{R T_1 P_2} \right) = 8.6 \quad \text{Area ratio should be 5.1}$$



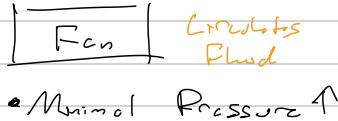
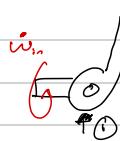
2) Compressors / Turbines



- As $P \uparrow$, so does T_{mp}



- As $P \uparrow$, only slight $T_{\text{mp}} \uparrow$



- Minimal Pressure \uparrow

Example 6-42

Conditions provided for adiabatic steam turbine



$$\begin{aligned} P_1 &= 10 \text{ MPa} \\ T_1 &= 500^\circ\text{C} \end{aligned}$$

$$w_{\text{out}} = \dot{m} (h_1 - h_2)$$

$$\left. \begin{array}{l} P_1 \\ T_1 \end{array} \right\} \begin{array}{l} \text{Steam} \\ \text{Turbine} \end{array} \xrightarrow{\text{SH}} h_1 = 3328 \frac{\text{kJ}}{\text{kg}}$$

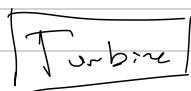
$$\left. \begin{array}{l} P_2 \\ \text{low } P_a \end{array} \right\} \begin{array}{l} \text{Subcooled} \\ \text{Water} \end{array} \xrightarrow{\text{SH}} h_g = 191.82 \frac{\text{kJ}}{\text{kg}}$$

$$h_f = 2583.9 \frac{\text{kJ}}{\text{kg}}$$

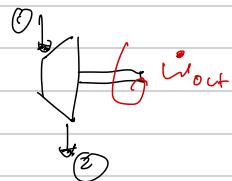
$$h_2 = h_g + x(h_f - h_g) = 2344.2 \frac{\text{kJ}}{\text{kg}}$$

- Find w_{out} for $\dot{m} = 2 \frac{\text{kg}}{\text{s}}$

$$w_{\text{out}} = 2 \frac{\text{kg}}{\text{s}} (3328 - 2344.2) \frac{\text{kJ}}{\text{kg}} = 2061 \text{ kW} = 2.06 \text{ MW}$$



- Extracts fluid power to produce shaft work



Energy Analysis

$$\dot{Q}_{\text{net,in}} + \dot{W}_{\text{net,in}} = \dot{m} [h_{\text{in}} - h_{\text{out}} + \frac{1}{2}(v_{\text{2}}^2 - v_{\text{1}}^2) + g(z_{\text{2}} - z_{\text{1}})]$$

Assumptions: $\Delta PE \approx 0$

Reduces friction \dot{Q} typically small

$\Delta KE \approx 0$ desired result

KE converted to Enthalpy P_v via losses devices

Focuses on \dot{Q} vs \dot{W}

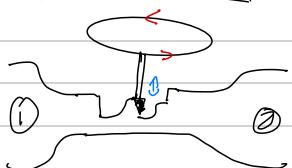
$$\dot{W}_{\text{net,in}} = \dot{m} (h_1 - h_2)$$

$$\dot{W}_{\text{in}} - \dot{W}_{\text{out}} = \dot{m} (h_1 - h_2)$$

3) Throttles \rightarrow Valve



Controls Flow, Control Pressure



$$Q_{\text{Net}} + \dot{W}_{\text{Net}} = m [(h_2 - h_1) + \frac{1}{2} (V_2^2 - V_1^2) + g (z_2 - z_1)]$$

$$\text{Assumptions: } \Delta P_E \approx 0$$

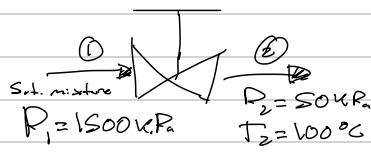
$$\Delta K_E \approx 0$$

$$\dot{Q}_{\text{Net}} \approx 0$$

$$\dot{W}_{\text{Net}} \approx 0$$

$$\text{enthalpy conserved: } h_1 = h_2, P_1 > P_2$$

Example: Steam flowing through a valve



$$P_1 = 1500 \text{ kPa}, T_1 = 100^\circ\text{C}$$

$$P_2 = 500 \text{ kPa}, T_2 = 100^\circ\text{C}$$

Find \dot{Q}_{add} @ inlet

$$\text{1st law: } h_1 = h_2$$

$$P_2 \underset{\substack{\text{Steam} \\ \text{Turb}}}{\gtrsim} \underset{\text{Tables}}{\gtrsim} h_2 = 2682.4 \frac{\text{kJ}}{\text{kg}} = h_1$$

$$h_1 = 2684.2 \underset{\substack{\text{Steam mix} \\ P_1 = 1500 \text{ kPa}}}{\gtrsim} h_1 = h_g + x(h_f - h_g) \Rightarrow x = \frac{h_1 - h_g}{h_f - h_g}$$

$$h_f = 844.85 \frac{\text{kJ}}{\text{kg}}$$

$$h_g = 2791.0 \frac{\text{kJ}}{\text{kg}}$$

$$\Rightarrow x = 0.49$$

Recap

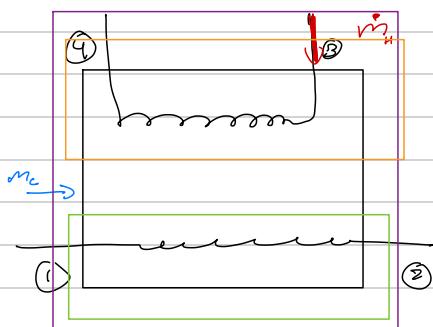
$$(i) \text{ Nozzles / Diffusers} \quad (h_2 - h_1) + \frac{1}{2} (V_2^2 - V_1^2) = 0$$

$$(ii) \text{ Compressors / Turbines} \quad \dot{W}_{\text{Net}} = m (h_2 - h_1)$$

$$(iii) \text{ Turbines} \quad h_1 = h_2$$

Heat Exchangers

Transfers heat from hotter fluid to colder fluid



$$\text{Energy Analysis: } Q_{\text{in}} - Q_{\text{out}} + (h_1 - h_2) = m [(h_2 - h_1) + \frac{1}{2} (V_2^2 - V_1^2) + g (z_2 - z_1)]$$

$$\text{Assumptions: } \dot{W}_{\text{Net}} = 0, \Delta P_E \approx 0$$

$$\Delta K_E \approx 0$$

If Boundary is Purple

$$Q_{\text{out}} = m_H (h_2 - h_1) + m_C (h_2 - h_1)$$

If Boundary is Green

$$Q_{\text{in}} = m_C (h_2 - h_1)$$

$$Q_{\text{in}} = Q_{\text{out}}$$

$$m_C (h_2 - h_1) = m_H (h_2 - h_1)$$

If Boundary is Orange

$$Q_{\text{out}} = m_H (h_2 - h_1)$$

Second Law of Thermodynamics

1st Law: Accounting of Energy

Implications of the 2nd Law

- (i) Processes proceed spontaneously (naturally) in a particular direction
- (ii) Energy has quality, not just quantity
↳ 2nd Law ↳ 1st Law
- (iii) Sets limits on theoretical performance
- (iv) Helps determine degree of chemical reaction completion

Ways to Quantify the 2nd Law

- (i) Heat Engine \rightarrow energy conversion
- (ii) Entropy - measure of disorder

Heat Engines: Device that converts heat into work

Example: Steam Power Plant, Car Engine,

- Consists of 4 key elements

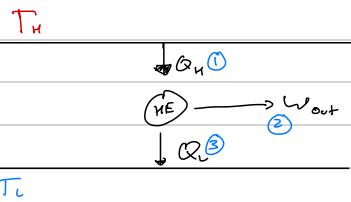
(i) Receives heat from a high-Temp Reservoir at T_H

(ii) Converts a portion of the heat \rightarrow work

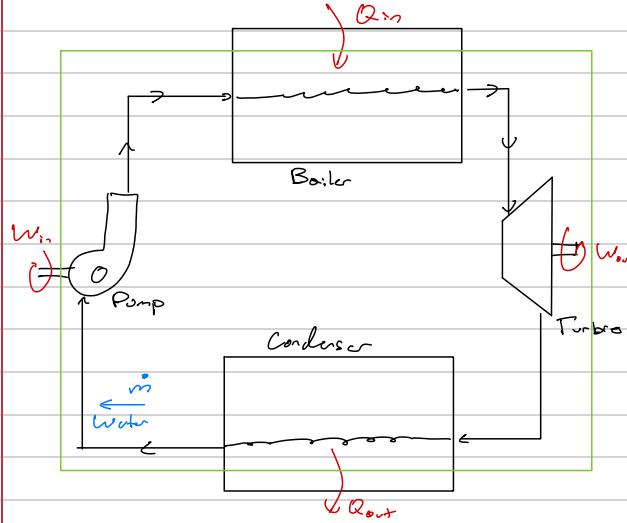
(iii) Rejects heat to a low-temp reservoir at T_L

(iv) Operates as a cycle

↓ Irreversible ↓ Reversible



Power Plant as a heat engine (Rankine Cycle)



1st Law Analysis

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m(c_2 - c_1)$$

boiler condenser pump turbine

Operates as a cycle

$T_H \sim$ Combustion Temperature

$$Q_H = Q_{in}$$

$$Q_L = Q_{out}$$

$T_L \sim$ River, Ocean, Lake Etc...

- Define Thermal Efficiency

$$\eta_{th} = \frac{W_{net,out}}{W_{net,in} - W_{pump}} = \frac{W_{net,out}}{Q_{in}} \Rightarrow \eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} - \frac{Q_L}{Q_{in}}$$

2nd Law

Typical Thermal Efficiencies

- Car Engine (spark ignition): $\eta_{th} = 25-30\%$

- Diesel Engine: $\eta_{th} \approx 40\%$

- Combined Cycle Power Plant (gas turbine + steam turbine): $\eta_{th} \approx 60\%$

Two Statements of the 2nd Law

1) Kelvin-Planck Statement

a) Impossible to generate work from a single reservoir



In other words, we must reject some heat

b) $\eta_{th} \neq 1$; Thermal Efficiency is never 100%!

→ Define the ideal heat engine

↪ Carnot Cycle

• Form ideal heat engine from ideal processes

Ideal Process → Reversible Process: A process that can be reversed without impact on the surroundings

→ Idealizations on an actual process

• Pump - reversible compression: Requires minimum work

• Turbine - reversible expansion: Produces maximum work

→ Some irreversibilities

(i) Chemical Reactions

(ii) Heat Transfer through a finite temperature difference

(iii) Inelastic deformations

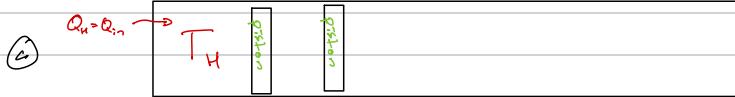
(iv) Friction (or losses)

(v) Mixing of dissimilar fluids

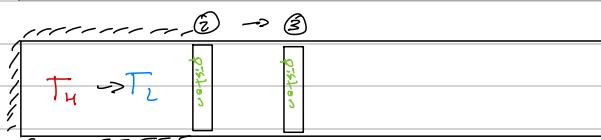
(vi) Electrical Resistance

→ Carnot Heat Engine (Ideal Heat Engine)

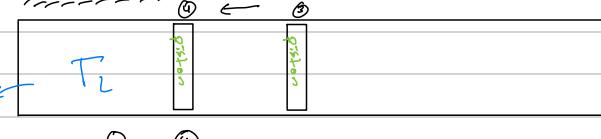
① → ②



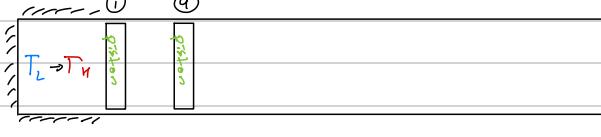
⑤



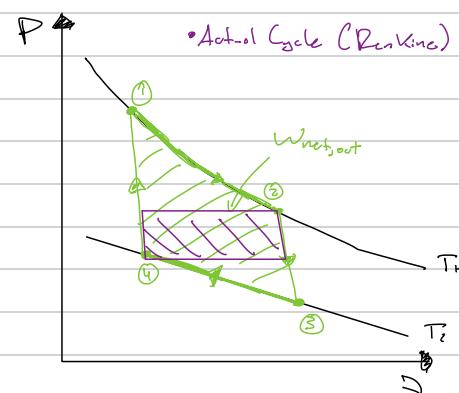
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⑦



Actual Cycle (Rankine)



$$W_{piston} = \int P dV$$

Area under or above curve

Actual Steps in Cycle

a) Isenthalpic expansion @ TH
b) Adiabatic expansion: $T_H \rightarrow T_L$

Cooling

Pump

c) Isenthalpic compression @ T_L
d) Adiabatic compression

Carnot Principles

- 1) Efficiency of an irreversible (Carnot, real) cycle is always less than a reversible cycle operating between T_H and T_L .
- 2) Efficiency of all reversible engines acting between T_H and T_L is the same.

- Introduce the thermodynamic (absolute) temperature

$$\left(\frac{Q_H}{Q_L} \right)_{rev} = \left(\frac{T_H}{T_L} \right)_{absolute}$$

→ For a heat engine (general):

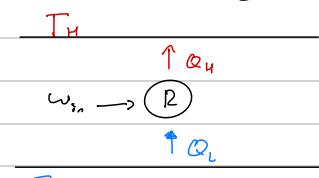
$$\eta_{th} = \frac{w_{net,out}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

→ For a Carnot heat Engine:

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H} \quad \text{3 must be absolute}$$

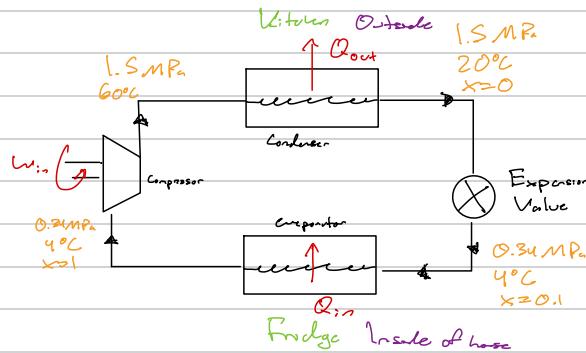
Refrigeration Cycles & Heat Pumps

Refrigeration Cycle



Example values in orange

onto cycle to the right



Valid for:

- Refrigerators
- Air conditioners

1st Law

$$w_{in} + Q_L = Q_H$$

$$(w_{in} = Q_H - Q_L)$$

Coefficient of Performance (COP)

$$COP_R = \frac{Q_{in}}{w_{in}} = \frac{Q_L}{w_{in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1} \Rightarrow COP_R > 1$$

also based on 1st Law Relationship

Typical Values: $COP_R = [2, 6]$ ← Higher COP_R is better, less work needed

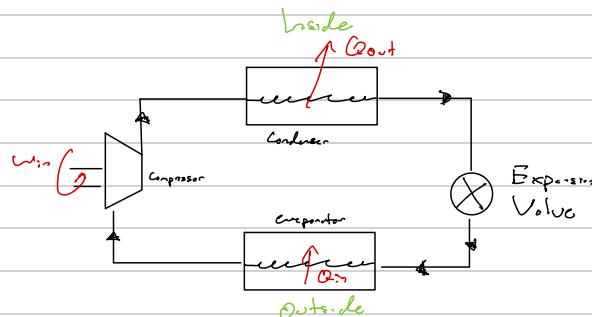
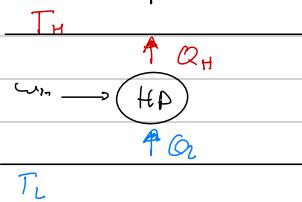
$$\rightarrow \text{Generally: } COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Apply Thermodynamic temp. Scale

$$\rightarrow \text{Ideal (Carnot) refrigerator: } COP_{R,ideal} = \frac{1}{\frac{T_H}{T_L} - 1} \leftarrow COP_R \text{ based on reservoir temps!}$$

Note that $COP_{R,ideal} > COP_R, \text{ generally}$

Heat Pump



Coefficient of Performance

$$COP_{HP} = \frac{Q_{out}}{w_{in}} = \frac{Q_H}{w_{in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

Typical Values: $COP_{HP} = [1, 2]$

$$\rightarrow \text{Ideal Heat Pump: } COP_{HP,ideal} = \frac{1}{1 - \frac{T_L}{T_H}}$$

Two Types of Heat Pumps

1) Air Source

↳ T_L is the air

2) Ground Source

↳ T_L is the ground

Example 2 - S3

- Heat Pump Cycle
- R134a enters condenser at 800 kPa and 35°C
- at $\dot{m} = 0.018 \frac{\text{kg}}{\text{s}}$ and leaves at 800 kPa as a saturated liquid.
- Compressor consumes 1.2 kW of power

Find (i) COP_{HP}

- (ii) Rate of heat absorption from the outside air

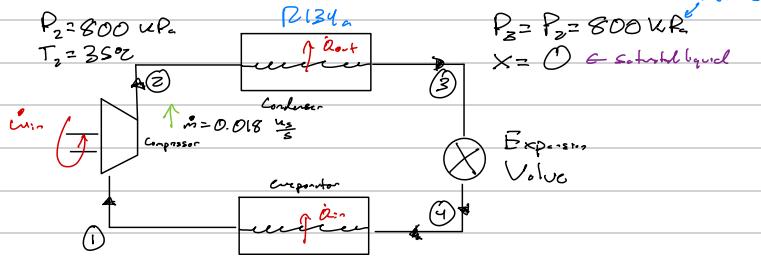
$$\text{COP}_{\text{HP}} = \frac{\dot{Q}_{\text{out}}}{\dot{w}_{\text{in}}} = ?$$

$$\text{COP}_{\text{HP}} = \frac{3.16}{1.2} = 2.64$$

$$\boxed{\text{COP}_{\text{HP}} = 2.64}$$

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{out}} + \dot{w}_{\text{in}} = 3.16 \text{ kW} - 1.2 \text{ kW} = 1.96 \text{ kW}$$

$$\boxed{\dot{Q}_{\text{in}} = 1.96 \text{ kW}}$$



$$W_{\text{in}} \text{ Given: } W_{\text{in}} = 1.2 \text{ kW}$$

1st Law, open system

$$\dot{Q}_{\text{out}} = \dot{m}(h_2 - h_3) = \dot{Q}_H$$

Tables: (i)

$$\begin{aligned} T_2 &= 35^\circ\text{C} \\ P_2 &= 800 \text{ kPa} \end{aligned} \quad \left. \begin{array}{l} \xrightarrow{\text{SH}} h_{310} = \dots \\ h_{400} = \dots \end{array} \right. \begin{array}{l} \text{Interpolate} \\ \text{to find } h_2 \end{array} \quad h_2 = 271.2 \frac{\text{kJ}}{\text{kg}}$$

$$\begin{aligned} \text{From R134a tables} \\ \text{At } P_3 = 800 \text{ kPa} \end{aligned} \quad (ii)$$

$$\begin{aligned} x = 0 \\ A = 1 \end{aligned} \quad \left. \begin{array}{l} \xrightarrow{\text{in opp.}} h_f = h_2 = 24.48 \frac{\text{kJ}}{\text{kg}} \\ h_{400} = \dots \end{array} \right. \begin{array}{l} \xrightarrow{\text{Shaded}} h_2 = h_3 = 24.48 \frac{\text{kJ}}{\text{kg}} \\ \text{Liquified} \end{array}$$

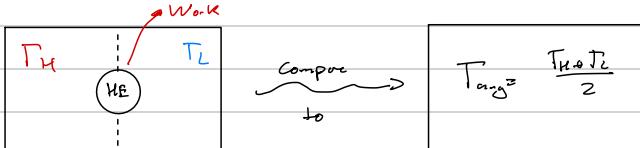
$$\rightarrow \dot{Q}_H = \dot{m}(h_2 - h_3) = 3.16 \text{ kW} = \dot{Q}_{\text{out}}$$

Entropy

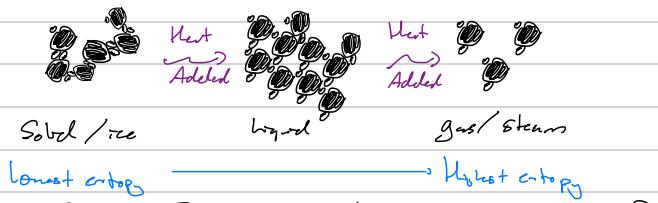
- For cycles / processes
 - Ideal cycles/processes \rightarrow reversible
 - Real cycles/processes \rightarrow irreversible
- Irreversibility \Rightarrow entropy generation

Want to think about entropy

(i) Entropy change as a measure of energy quality/ degradation



(ii) Entropy as a measure of molecular system disorder



• Define Entropy change based on heat transfer for an initially reversible process

$$dS = \left(\frac{dQ}{T} \right)_{ideal}$$

↓ Total change $\left\{ \frac{dQ}{dT} \right\}_{process}$

Make sure you're using absolute temperature!

\hookrightarrow Mass specific basis: $dS = \frac{dS}{m} \left\{ \frac{dQ}{m} \right\}$

For a real process: $dS > \frac{dQ}{T}$

• Integrate to get total entropy change for a process

$$\Delta S = \int_1^2 \frac{dQ}{T} \quad \text{would need to know how } Q \text{ & } T \text{ are related}$$

• System in its surroundings



$\rightarrow dS$ can be positive or negative depending on the sign of dQ

\rightarrow Assume surroundings are isolated

No heat or work out of the surroundings

• Total Entropy change is always positive

$$\Delta S_{total} = \Delta S_{sys} + \Delta S_{surroundings}$$

Three Possibilities

(i) $\Delta S_{tot} > 0 \Rightarrow$ real process (impossible)

(ii) $\Delta S_{tot} = 0 \Rightarrow$ ideal process (reversible)

(iii) $\Delta S_{tot} < 0 \Rightarrow$ impossible!

• For a real system:

$$\Delta S_{sys} = \int_1^2 \left(\frac{dQ}{T} \right)_{ideal} + S_{generated}$$

$$\Delta S_{tot} = \int_1^2 \left(\frac{dQ}{T} \right)_{sys, real} + \int_1^2 \left(\frac{dQ}{T} \right)_{sur, ideal} + S_{generated}$$

entropy generated through irreversibilities

Calculating Entropy Change

1) Isothermal Process (valid for surroundings)

Assume fixed temperature T_0

$$\Delta S_{\text{sur}} = \int_{1,}^2 \frac{dQ}{T} \geq \int_{1,}^2 \frac{dG}{T_0} = -\frac{Q_2}{T_0}$$

Heat Transfer from 1 to 2

2) More Generally

$$dQ - dw = du$$

$(P_{\text{in}} - P_{\text{out}})$ $(w = -PdV)$ \downarrow Change in energy

$$dS \frac{dQ}{T} + T dS - P dV = du$$

\downarrow Divide by mass: \downarrow lower case vars for division by mass

$$TdS = du + PdV$$

Gibbs Equations

Gibbs Equations - enthalpy form

$$TdS = du + PdV$$

• Recall: $h = u + Pv$

$$\begin{aligned} \rightarrow dh &\equiv du + d(PV) \\ &= du + PdV + VdP \\ \Rightarrow dh &= du - PdV - VdP \end{aligned}$$

$$TdS = dh - PdV - VdP$$

$$TdS = dh - VdP$$

• Evaluating ΔS

1) Phase change fluids

→ Use tables for s_1, s_2

$$\Delta S_{\text{sys}} = s_2 - s_1$$

2) Ideal Gases

$$TdS = du + PdV$$

$$\rightarrow \text{Ideal Gas EoS: } PV = RT \Rightarrow P = \frac{RT}{V}$$

$$TdS = du + \frac{RTdV}{V}$$

$$\rightarrow \text{(ideal gas) Internal Energy } \rightarrow dU = C_V dT$$

$$TdS = C_V dT + \frac{RTdV}{V}$$

$$ds = C_V \frac{dT}{T} + R \frac{dV}{V}$$

→ Integrate and assume C_V is a constant

$$\Delta S_{\text{sys}} = C_V, \text{Avg} \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{V_2}{V_1} \right)$$

If we started with enthalpy form:

$$\Delta S_{\text{sys}} = C_p, \text{Avg} \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right)$$

Equally valid, choose baselines of your quantities

3) True (Incompressible) liquids/solids

$$TdS = du + PdV \xrightarrow{\text{Incompressible}} dV \approx 0$$

$$TdS = dh - VdP \xrightarrow{\text{Incompressible}} dP \approx 0$$

$$\rightarrow TdS = C_V dT \quad \left\{ C_V = C_P = C \text{ for these substances} \right.$$

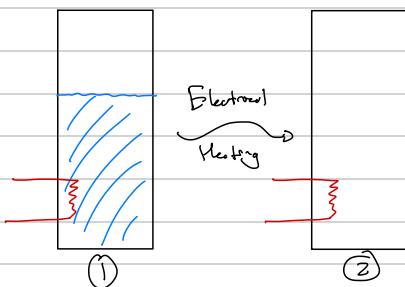
$$\rightarrow TdS = C dT$$

→ Integrate:

$$\Delta S_{\text{sys}} = C \ln \left(\frac{T_2}{T_1} \right)$$

Exams will be more approachable based instead of derivative based

Example 8-30) Un-insulated tank $K \approx 3 \text{ kg/m}$



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

$\frac{3}{4}$ of mass is liquid
↓

All vapor (\approx superheat)

$$\gamma_2 = \gamma_1$$

$$\text{Find: } \Delta s_{\text{sys}}$$

Stat at tables:

$$\sum \frac{\delta Q}{T}$$

$$Q_{\text{add}} \quad \text{at } 1^\circ \quad x_1 = \frac{1 - \gamma_{\text{sat}}}{1 + \gamma_{\text{sat}}} = 0.25$$

$$P_1 \quad \left. \begin{array}{l} \xrightarrow{\text{sat.}} S_f = 1.8302 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ \xrightarrow{\text{mix}} S_g = 7.127 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \end{array} \right\} \quad S_i = x_1 S_{\text{sat}} (1 - x_1) S_p = 2.9294 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

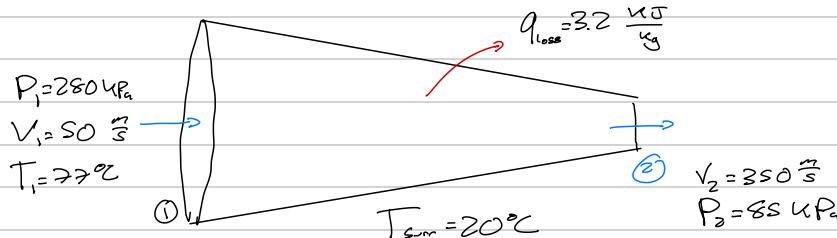
$$\left. \begin{array}{l} \xrightarrow{\text{sat.}} \gamma_f = 0.001061 \frac{\text{m}^3}{\text{kg}} \\ \xrightarrow{\text{mix}} \gamma_g = 0.88578 \frac{\text{m}^3}{\text{kg}} \end{array} \right\} \quad \gamma_i = x_1 \gamma_g + (1 - x_1) \gamma_f = 0.222 \frac{\text{m}^3}{\text{kg}}$$

$$Q_{\text{add}} \quad \text{at } 2^\circ \quad x_2 = 1, \text{ all v.p.} \quad \checkmark \text{ Inert prop.}$$

$$\gamma_2 = 0.222 \frac{\text{m}^3}{\text{kg}} \quad \left. \begin{array}{l} \xrightarrow{\text{sat.}} S_i = S_g = 6.63 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ x_2 = 1 \end{array} \right\} \quad \text{Look for } 0.222 \frac{\text{m}^3}{\text{kg}} \text{ on Res. or Temp tables}$$

$$\rightarrow \Delta s_{\text{sys}} = m(S_2 - S_1) = +11.1 \frac{\text{kJ}}{\text{kg}} \quad \text{← added heat, entropy should increase}$$

Example 8-81) Entropy change for air in a nozzle



$$\text{Find: } \text{a) } T_2$$

$$\text{b) } \Delta s_{\text{total}}$$

$$\sum \frac{\delta Q}{T}$$

$$\text{1st Law: } (Q_{\text{in}} - Q_{\text{out}}) + (C_v \ln \frac{T_2}{T_1}) = m [(h_2 - h_1) + \frac{1}{2} (v_2^2 - v_1^2)]$$

$$\text{Dissipation: } -q_{\text{loss}} = (h_2 - h_1) + \frac{1}{2} (v_2^2 - v_1^2)$$

$$\text{Treat as Ideal: } -q_{\text{loss}} = c_{\text{p,avg}} (T_2 - T_1) + \frac{1}{2} (v_2^2 - v_1^2) \quad \text{Table: } c_{\text{p,avg}} = 1005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$\text{Plug in: } T_2 = 24.11^\circ\text{C}$$

For total entropy change: $\Delta s_{\text{tot}} = \Delta s_{\text{sys}} + \Delta s_{\text{sur}}$

System given pressure, use enthalpy form

$$\Delta s_{\text{sys}} = C_{\text{p,avg}} \ln \left(\frac{T_2}{T_1} \right) - R_{\text{air}} \ln \left(\frac{P_2}{P_1} \right) \xrightarrow{\text{Plug}} \Delta s_{\text{sys}} = 0.18 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$\downarrow 1005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \quad \text{absolute} \quad R_{\text{air}} = 0.2870 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Surroundings treat surroundings as isothermal

$$\Delta s_{\text{sur}} = \frac{Q}{T_0} \quad \left| \begin{array}{l} \text{use} \\ \text{constant w.r.t. surroundings} \end{array} \right. \quad \Delta s_{\text{sur}} = \frac{+3.2}{20 + 273.15} \frac{\text{kJ}}{\text{kg}\cdot\text{K}} = 0.01 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Total

$$\Delta s_{\text{tot}} = 0.18 + 0.01 = 0.19 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \Rightarrow \text{Real since } \Delta s_{\text{tot}} > 0$$

$$\boxed{\Delta s_{\text{tot}} = 0.19 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}}$$

1. Isentropic Processes

- $\Delta s_{isent} = 0$

$$\Rightarrow \Delta s_{isent} = s_2 - s_1 = 0 \Rightarrow s_2 = s_1$$

- By substance type

(i) Phase Change fluids \rightarrow tables

$$\Rightarrow s_2 = s_1$$

(ii) Ideal Gases

$$\Delta s_{isent} = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right) \xrightarrow{\text{Due to being isentropic}}$$

$$\Rightarrow \ln\left(\frac{T_2}{T_1}\right) = -\frac{R}{c_v} \ln\left(\frac{V_2}{V_1}\right) \rightarrow \ln\left(\frac{T_2}{T_1}\right) = \ln\left[\left(\frac{V_1}{V_2}\right)^{R/c_v}\right]$$

- Ratio of specific heats: $K = \frac{C_p}{C_v}$

- For ideal gases: $R = C_p - C_v$

$$\therefore \ln\left(\frac{T_2}{T_1}\right) = \ln\left[\left(\frac{V_1}{V_2}\right)^{K-1}\right] \Rightarrow \frac{T_{2s}}{T_1} = \left(\frac{V_1}{V_2}\right)^{K-1}$$

This is ok true for an ideal gas in an isentropic process

Take T_{2s} as output of process

- Start with enthalpy for ...

$$\Delta s_{isent} = c_{p,avg} \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \xrightarrow{\text{isentropic process}}$$

Similar algebra

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}$$

Derived similarly with $K = \frac{C_p}{C_v}$ & $\frac{R}{c_v} = K-1$

- Combine specific volume expression with enthalpy one...

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

Also valid only for ideal gases in an isentropic process

Caution: watch out for assumptions when problem-solving

- True Liquids/Solids

$$\Delta s_{isent} = C \ln\left(\frac{T_2}{T_1}\right) \xrightarrow{\text{isentropic}}$$

$$C \ln\left(\frac{T_2}{T_1}\right) = 0$$

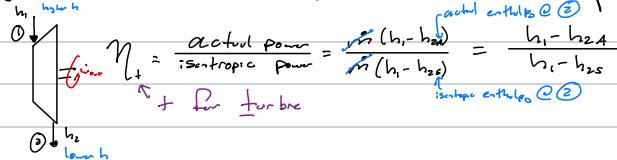
For solids/incompressible liquids, process must be isothermal to be isentropic

$\leftarrow T_2 = T_1$ to be true!

- Use isentropic processes to define process/component efficiency

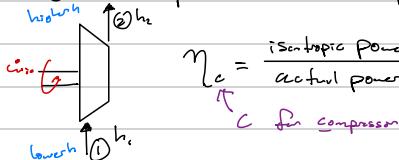
\Rightarrow Isentropic Efficiency

(i) Turbines - isentropic turbine will produce the most power (largest possible fraction)



$$\eta_t = \frac{h_1 - h_{2s}}{h_1 - h_2}$$

(ii) Compressors - isentropic compressor will require the least power



$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Example 8-118) Adiabatic CO_2 Compressor

State 1: $P_1 = 100 \text{ kPa}$, $T_1 = 300 \text{ K}$, $m = 1.8 \frac{\text{kg}}{\text{s}}$

State 2: $P_2 = 600 \text{ kPa}$, $T_2 = 450 \text{ K}$

$\eta_c = \frac{h_{2s} - h_1}{h_{2A} - h_1} = \frac{C_{PAg} (T_{2s} - T_1)}{C_{PAg} (T_{2A} - T_1)}$

$T_{2s} = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\kappa-1}{\kappa}}$ $\xrightarrow[\text{CO}_2]{\text{Tables}} \kappa = 1.2635$

$\Rightarrow T_{2s} = 434.2 \text{ K}$

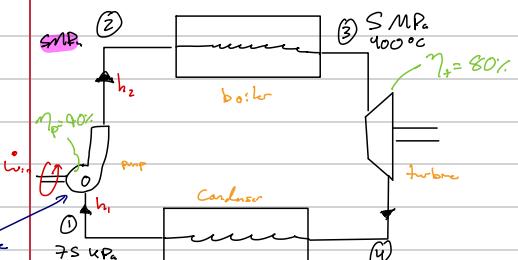
$\therefore \eta_c = \frac{(434.2 \text{ K} - 300 \text{ K})}{(450 \text{ K} - 300 \text{ K})} = 0.895$

$\eta_c = 89.5\%$

What type of fluid does have exiting the turbine? Sat. Mixture but mostly vapor. 1 pt

Review Lecture

Example Steam Power Plant (Rankine cycle) ← 4 components



$$\eta_{th} = 1 - \frac{\dot{Q}_out}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$\eta_{isentropic} = 1 - \frac{T_2}{T_1}$$

State ①

$$P_1 = 75 \text{ kPa} \xrightarrow{\text{sat}} T_1 = 91.76^\circ\text{C}, s_p = s_1 = 1.2132 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_1 = 0 \quad h_1 = h_f = 384.44 \frac{\text{kJ}}{\text{kg}}$$

- Final η_{th} compared to $\eta_{isentropic}$

Boiler & compressor are both isobaric (constant P)

$$\dot{W}_{pump} = \dot{V}_{in} = \dot{m}(h_{2A} - h_1)$$

(i) Isentropic compression from ① → ②

Looks at ~~both cases~~ - State ②: $s_2 = s_1 = 1.2132 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

Interpolation not on exam 3

- For actual pump:

$$\eta_p = \frac{h_{2A} - h_1}{h_{2A} - h_1} = 0.40$$

$$\Rightarrow h_{2A} = 390.74 \frac{\text{kJ}}{\text{kg}} \text{ vs. } h_{ss} = 390.107 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{W}_{pump} = \dot{m}(h_{2A} - h_1) = \dot{m}(6.3) \text{ kW}$$

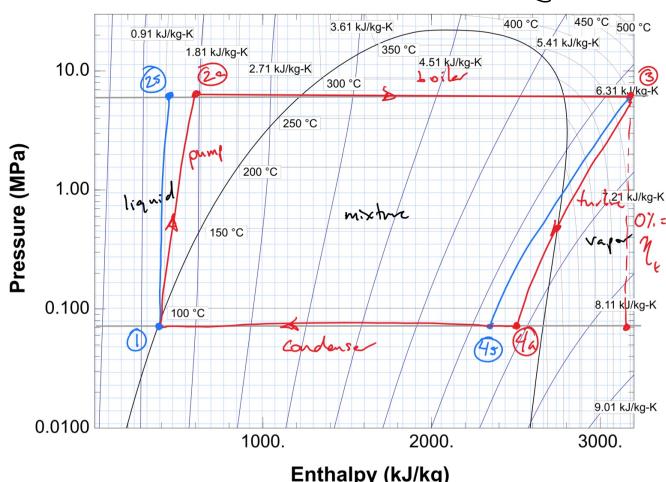
State ②

$$P_2 = SMPa \xrightarrow{\text{sat}} s_2 < s_{2A} < s_g \xrightarrow{\text{comp.}} h_{ss} = 390.107 \frac{\text{kJ}}{\text{kg}}$$

$$s_{80} < s_2 < s_{100}$$

interpolate

Pressure (MPa) vs. Enthalpy ($\frac{\text{kJ}}{\text{kg}}$) Plot



State ③

$$T_3 = 400^\circ\text{C} \xrightarrow{\text{sat}} h_3 = 3146.2 \frac{\text{kJ}}{\text{kg}}$$

$$P_3 = SMPa \xrightarrow{\text{sat}} s_3 = 6.6483 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Isentropic expansion from ③ → ④s

$$P_4 = 75 \text{ kPa} \xrightarrow{\text{sat}} x_{4s} = 0.871 \xrightarrow{\text{from } s_{4s}} h_{4s} = 2832.8 \frac{\text{kJ}}{\text{kg}}$$

$$\text{For actual turbine } \eta_t = \frac{h_3 - h_{4s}}{h_3 - h_{4s}} = 0.80$$

$$\Rightarrow h_{4s} = 2833.6 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{W}_{turbine} = \dot{W}_{out} = \dot{m}(h_3 - h_{4s}) = \dot{m}(663) \text{ kW}$$

Boiler heat addition:

$$\dot{Q}_{in} = \dot{m}(h_3 - h_{2A}) = \dot{m}(2806) \text{ kW}$$

Thermal Efficiency (η_{th})

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$= \frac{\dot{m}(663 - 6.8)}{\dot{m}(2806)} = 23.4\%$$

Carnot Efficiency (η_{carnot})

$$\eta_{carnot} = 1 - \frac{T_2}{T_1} \leftarrow \text{temp into pump } (T_{sat} @ 75 \text{ kPa})$$

$$\eta_{carnot} = 1 - \frac{T_2}{T_1} \leftarrow \text{temp into turbine}$$

$$= 1 - \frac{41.8 + 273.15}{400 + 273.15} = 45.8\%$$

Exam 2

