

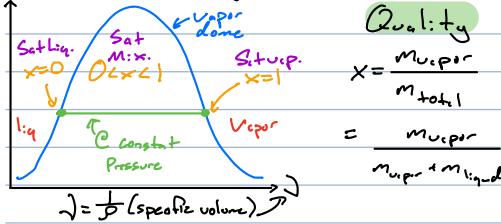
Modes of Energy Storage @ Microscale

- Structure @ Microscale defines macrostate of energy
- | | | |
|---|------------------------------------|---------------------|
| Sensible Modes Related to activity & motion | (i) Translational Motion (KE) | (ii) Phase Changes |
| | (iii) Vibrational Motion | (iv) Chemical Bonds |
| | (v) Rotational Motion | (vi) Nuclear Bonds |
| | Latent modes
Structural changes | |
| | (vii) Electron Translation | |

Energy can cross boundary as: (i) Heat (ii) Work (iii) Mass

Mass Flow Rate: $\dot{m} = \rho V_{avg} A_c$

Phase Change Fluids (Tables)



Quality

Quality

$$x = \frac{m_{vapor}}{m_{total}}$$

$$= \frac{m_{vapor}}{m_{vapor} + m_{liquid}}$$

Phase Regions

(i) Compressed Liquid

\rightarrow @ given P : $T < T_{sat}$

\rightarrow @ given T : $P > P_{sat}$

(ii) Saturated Liquid ($x=0$)

$\rightarrow T = T_{sat}$ & $P = P_{sat}$

(iii) Saturated Vapor ($x=1$)

$\rightarrow T = T_{sat}$ & $P = P_{sat}$

(iv) Superheated Vapor $\rightarrow T > T_{sat}$ & $P < P_{sat}$

(v) Subcooled Liquid $\rightarrow T < T_{sat}$ & $P < P_{sat}$

Closed Systems



$$1^{\text{st}} \text{ Law: } (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = U_2 - U_1 \quad \text{or} \quad \Delta U = Q + W$$

Can be an isobaric or isothermal process

Q_{in} : Heat Transfer into system

Q_{out} : Heat Transfer out of system

W_{in} : Work done on the system

W_{out} : Work done by the system

Boundary Work (Generally)

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

\hookrightarrow True for isobaric systems

$$W_{piston} = W_{out} \rightarrow W_{out} > 0 \text{ if volume } \uparrow$$

Polytropic Processes

$$PV^n = \text{Constant} \Rightarrow P_1 V_1^n = P_2 V_2^n \quad \& \quad W_{piston} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Ideal Gas EoS

Law: $PV = nRT$ \hookrightarrow Universal Gas Constant

EoS: $PV = mRT$ \hookrightarrow Particular Gas Constant

$$P = RT$$

$$R = \frac{P}{Mw}$$

Specific Volume \rightarrow

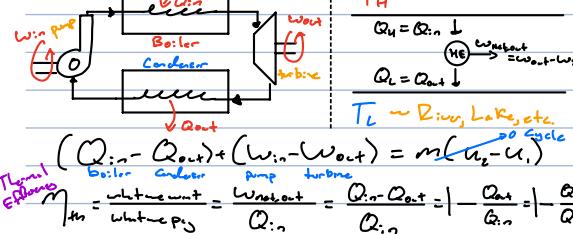
$$\bar{V} = \frac{1}{\rho} = \frac{V}{m} \Rightarrow m = \frac{V}{\bar{V}}$$

$$m = \frac{V}{\bar{V}} \quad \& \quad V = m \bar{V}$$

$$\bar{V} = \frac{1}{\rho} = \frac{V}{m}$$

$$\bar{V} = \frac{1}{\$$

Rankine Cycle Power plant as a heat engine



Carnot Principles Carnot cycles are ideal cycles/conditions

(i) Efficiencies of an irreversible (real) cycle is always less than a reversible cycle

(ii) Efficiency of all reversible engines acting between T_H and T_L is the same

$\Rightarrow \left(\frac{Q_H}{Q_L} \right)_{rev} = \left(\frac{T_H}{T_L} \right)_{ideal} \rightarrow \eta_{Carnot} = 1 - \frac{T_L}{T_H} \leftarrow \text{must be absolute from } \eta_{th} = 1 - \frac{Q_L}{Q_H}$

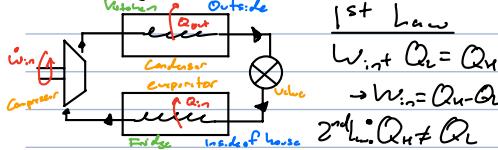
Carnot Heat Engine

- (i) Isothermal expansion @ T_H (iii) Isothermal compression @ T_L
- (ii) Adiabatic expansion: $T_H \rightarrow T_L$ (iv) Adiabatic compression

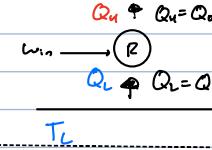
$$CoP_{Carnot} = \frac{1}{\frac{T_L}{T_H} - 1}$$

$$CoP_{HP, Carnot} = \frac{1}{1 - \frac{T_L}{T_H}}$$

Refrigeration cycle valid for fridges, ACs

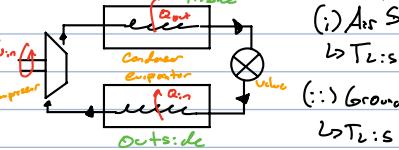


T_H

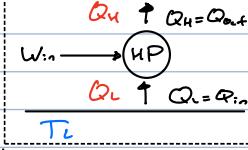


T_L

Heat Pump



T_H



T_L

Entropy

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

(ii) Entropy as a measure of molecular system disorder \leftarrow more microstates \rightarrow more entropy

For an Internally Reversible Process

$$dS = \left(\frac{dQ}{T} \right)_{\text{ideal}} \quad dS = \frac{ds}{T} \text{ mass specific}$$

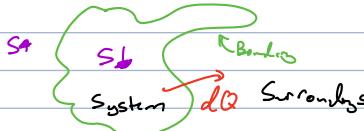
Total Entropy Change always nonnegative

$$\Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{sur}}$$

(i) $\Delta S_{\text{tot}} > 0 \Rightarrow$ real / reversible

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

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



Evaluating ΔS

1) Ideal Gases

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

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

1) Isentropic Processes $\Delta S_{\text{sys}} = 0 \rightarrow S_2 = S_1$

1) Ideal Gases

$$\frac{T_{2s}}{T_1} = \left(\frac{V_1}{V_2} \right)^{\kappa-1} \quad R = C_p - C_v$$

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{1}{\kappa-1}} \quad \kappa = \frac{C_p}{C_v}$$

All 3 valid
only for an
ideal gas in an
isentropic process

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

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1} \right)^{\frac{1}{\kappa-1}}$$

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1} \right)^{\frac{1}{\kappa-1}}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2} \right)^{\kappa-1}$$

$$\frac{P_2}{P_1} = \left(\frac{C_p}{C_v} \right)^{\frac{1}{\kappa-1}}$$

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1} \right)^{\frac{1}{\kappa-1}}$$

ECHE225 HW1

1. [Chapter 3] Consider a room that is held at a constant temperature of 20°C. The room contains six 14.5-W lightbulbs, a 2-kW electric oven, and a 200-W refrigerator. Assuming no heat transfer through the walls, determine the rate at which an air conditioning unit must remove heat from the room when all of these devices are on.

$$6 @ 14.5 \text{ W} \\ 1 @ 2000 \text{ W} \\ 1 @ 200 \text{ W}$$

$$\sum 2000 + 200 + 87 = 2287 \text{ W}$$

2. [Chapter 3] A fan is to accelerate quiescent air to a velocity of 8 m/s at a rate of 10.62 kg/s. If 30 W of the supplied power is turned into heat, determine the minimum power that must be supplied to the fan.

$$V_1 = 0 \\ V_2 = 8 \text{ m/s} \\ \dot{m}_{air} = 1.18 \frac{\text{kg}}{\text{m}^3} \cdot 10.62 \frac{\text{kg}}{\text{s}} = 12.5316 \frac{\text{kg}^2}{\text{m}^3 \cdot \text{s}}$$

$$q_v = 10.62 \frac{\text{kg}}{\text{s}} \\ P = 1.18 \frac{\text{kg}}{\text{m}^3}$$

$$E_{mech} = \dot{m} \left(\frac{P}{\dot{m}} + \frac{V^2}{2} + gz \right)$$

$$= 12.5316 \frac{\text{kg}}{\text{m}^3 \cdot \text{s}} \left(\frac{8^2 - 0^2}{2} \frac{\text{m}^2}{\text{s}^2} \right)$$

$$= 401.01 \frac{\text{kg}^2}{\text{m} \cdot \text{s}^3}$$

$$401.01 - 30 \text{ W} = 370 \text{ W}$$

*From
Question*

2. [Chapter 3] A fan is to accelerate quiescent air to a velocity of 8 m/s at a rate of 10.62 kg/s. If 30 W of the supplied power is turned into heat, determine the minimum power that must be supplied to the fan.

$$\rightarrow 8 \text{ m/s} \\ \rightarrow 10.62 \frac{\text{kg}}{\text{s}}$$

$$(W_{in} - W_{out}) + (E_{in} - E_{out}) = \frac{dE}{dt} \xrightarrow{\text{No change over time}}$$

$$W_{flow} = \frac{1}{2} \dot{m} V^2$$

Rate of flow ($\frac{\text{kg}}{\text{s}}$)

$$= \frac{1}{2} (10.62)(8)^2 = 340 \text{ W}$$

$$\frac{1}{2} \left(\frac{\text{kg}}{\text{s}} \right) \left(\frac{\text{m}}{\text{s}} \right)^2 = \frac{\text{kg} \cdot \text{m}^2}{\text{s}^3}$$

$$W_{in} = W_{flow} + 30 \text{ W} = 370 \text{ W}$$

3. [Chapter 3] A homeowner is considering these heating systems for heating their house:

- Electric resistance heating at \$0.12/kWh (1 kWh = 3600 kJ)
- Natural gas heating at \$1.22/therm (1 therm = 105,500 kJ)
- Oil heating at \$2.35/gal (1 gal of oil = 138,500 kJ)

Assuming efficiencies of 100% for the electric furnace and 87% for oil and gas furnaces, determine the heating system with the lowest cost.

Electric	Gas	Oil
$\$0.12/\text{kWh}$	$\frac{\$1.22}{\text{therm}} \times \frac{1 \text{ therm}}{105,500 \text{ kJ}} \times .87$ $= \$1 \times 10^{-5}/\text{kJ}$	$\frac{\$2.35}{\text{gal}} \times \frac{1 \text{ gal}}{138,500 \text{ kJ}} \times .87$ $= \$1.48 \times 10^{-5}/\text{kJ}$
Gas is cheapest		

4. [Chapter 5] A rigid container equipped with a stirring device contains 1.5 kg of motor oil. Determine the rate of specific energy increase when heat is transferred to the oil at a rate of 1 W and 1.5 W of power is applied to the stirring device.

$$\begin{aligned}
 m &= 1.5 \text{ kg} & \Delta \dot{E} &= \dot{Q} + \dot{W} & r &= \frac{\Delta \dot{E}}{m} \\
 \dot{Q} &= 1 \text{ W} & &= 1 \text{ W} + 1.5 \text{ W} & &= \frac{2.5 \text{ W}}{1.5 \text{ kg}} \\
 \dot{W} &= 1.5 \text{ W} & &= 2.5 \text{ W} & &= 1.67 \text{ W/kg}
 \end{aligned}$$

3. Given

Appliances: +9,000 kJ/hr

Building: Losses 75,000 kJ/hr

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

$$Q_{in} : 9,000 \text{ kJ/hr}$$

$$Q_{out} : 75,000 \text{ kJ/hr}$$

W_{in}: GeneratorW_{out}: None

Want to know

$$\Delta U = U_2 - U_1$$

$$\therefore \boxed{\Delta U = Q_{in} - Q_{out} + W_{in}}$$

$$1 \frac{\text{kJ}}{\text{s}} = 1 \text{ kW}$$

$$\Delta U = 9,000 \text{ kJ/hr} - 75,000 \text{ kJ/hr}$$

$$0 = -66,000 \text{ kJ/hr} + W_{in} \rightarrow W_{in} = 66,000 \text{ kW}$$

$$66,000 \frac{\text{kJ}}{\text{hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} \times \frac{1 \text{ kW}}{1 \frac{\text{kJ}}{\text{s}}} = \boxed{18.33 \text{ kW}}$$

Generator technically does work on system to keep it at a net 0
 Total Energy. Could be considered heat in (Q_n) as well given more information

→ The FULL 1st Law is $\Delta Q + \Delta W + \Delta E = \Delta U + \Delta KE + \Delta PE$

ECHE225 HW2

1. [Chapter 4] Complete this table for water.

T ($^{\circ}\text{C}$)	P (kPa)	v (m^3/kg)	u (kJ/kg)	x (if applicable)	Phase description
50	12.352	7.72	1643.15	0.642	Saturated mixture
143.61	400	0.46242	2553.1	1	Saturated vapor
110	350	0.00105	461.27	—	Compressed liquid
250	500	0.47443	2723.8	—	Superheated vapor

3 Sat. Liquid Table
→ Sat. Liquid
→ Superheated vapor

Quality not Applicable for superheated vapor and compressed liquid

Row 1

$$V = V_f + x(V_g - V_f) \quad u = u_f + x(u_g - u_f)$$

$$V_f = 0.001012 \quad \rightarrow x = \frac{V - V_f}{V_g - V_f} = 209.33 + .642(24427 - 209.33)$$

$$V_g = 12.026$$

$$u_f = 209.33 \quad = 7.72 - .001012$$

$$u_g = 2442.7 \quad 12.026 - .001012$$

$$x = 0.642$$

Row 2 Saturated Vapor $\rightarrow x = 1$

$$V_f = 0.01084 \quad u_f = 604.22 \rightarrow \text{Sat. Vapor, use } P_g$$

$$V_g = 0.46242 \quad u_g = 2553.1$$

Row 3

110°C is 143.38 kPa for sat. Pressure; $P > P_{\text{sat}}$ \rightarrow Compressed Liquid

- 350 kPa = 0.35 MPa

Recall: $u_{\text{cl}} = u_f(T)$ for Compressed Liquids

↙ Sat. Liquid value @ T

Ex. L. properties
Lar. based on sat.
liquid table + T^o

$$u_f = 461.27 \quad \text{and } V_f = 0.00105$$

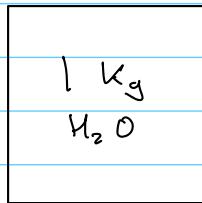
Row 4

250°C is 3976.2 kPa for Sat. Pressure, $P < P_{\text{sat}}$ \rightarrow Superheated vapor

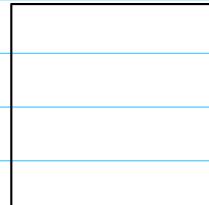
- 500 kPa = 0.5 MPa

$$J = 0.47443 \quad u = 2723.8$$

2. [Chapter 4] One kilogram of water fills a 150 L rigid container at an initial pressure of 2 MPa. The container is then cooled to 40°C. Determine the initial temperature and the final pressure of the water.



150L



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

$$T_1 =$$

$$P_2 =$$

$$T_2 = 40^\circ\text{C} = 313 \text{ K}$$

Sat. Water Table @ 2000 kPa:

$$T_{s,f} = 212.38$$

$$\gamma_f = 0.001177 \quad u_f = 906.12$$

$$\gamma_g = 0.044587 \quad u_g = 2544.1$$

Sat. Water Table @ 40°C:

$$P_{s,f} = 7.3851$$

$$\gamma_f = 0.001008 \quad u_f = 167.53$$

$$\gamma_g = 19.515 \quad u_g = 2429.4$$

$$150 \text{ L water} \times \frac{0.001 \text{ m}^3}{1 \text{ L}} = 0.15 \text{ m}^3$$

$$150 \text{ water} \times \frac{1 \text{ kg}}{1 \text{ L}} = 1 \text{ kg}$$

$$\bar{\gamma} = \left(\frac{m}{V}\right)^{-1} = \frac{V}{m} = \frac{0.15 \text{ m}^3}{1 \text{ kg}} = 0.15 \text{ m}^3/\text{kg}$$

$$\textcircled{1} \quad \gamma_f < \gamma_g < \bar{\gamma} \quad \text{so water is superheated}$$

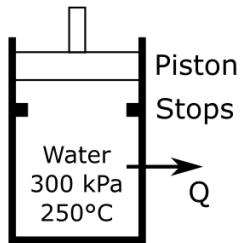
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Go to table
constant

$$T_1^\circ\text{C} \approx 400^\circ\text{C}$$

$$\textcircled{2} \quad \gamma_f < \bar{\gamma} < \gamma_g \quad \text{so water is saturated}$$

$$P_2 = 7.3851 \text{ kPa}$$

3. [Chapter 4] Water initially at 300 kPa and 250°C is contained in a piston-cylinder device fitted with stops. The water is allowed to cool at constant pressure until it exists as a saturated vapor and the piston rests at the stops. Then the water continues to cool until the pressure is 100 kPa. On a $T-v$ diagram, sketch the process curve passing through the first, second, and third states. Label the T , P , and v values for the states. Find the overall change in the internal energy between the first and third states per unit mass of water.



D.o.t Dom Steam table		$i \rightarrow \text{Saturated}$ Cools	$S_1 + V_{\text{gas}}$	\rightarrow	$\boxed{\quad}$

$T_1 = 250^\circ\text{C}$
 $P_1 = 300 \text{ kPa}$
 $v = 0.7964 \text{ m}^3/\text{kg}$
 $u = 2728.90 \text{ J/kg}$

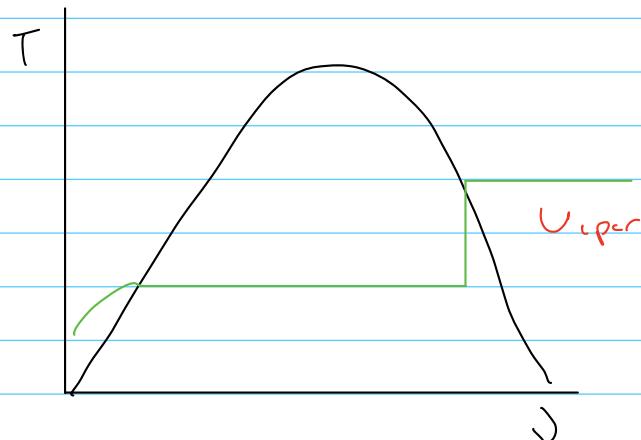
$T_2 = 133.52^\circ\text{C}$
 $P_2 = 300 \text{ kPa}$
 $v_g = 0.60882 \text{ m}^3/\text{kg}$
 $u_g = 2543.2 \text{ J/kg}$

$T_3 =$
 $P_3 = 100 \text{ kPa}$
 $v_f = 0.001043 \text{ m}^3/\text{kg}$
 $v_g = 1.6941 \text{ m}^3/\text{kg}$
 $u_f = 417.40 \text{ J/kg}$
 $u_g = 2505.6 \text{ J/kg}$

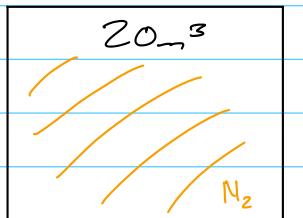
$x = \frac{v_g - v_{f3}}{v_{g3} - v_{f3}} = \frac{0.60882 - 0.001043}{1.6941 - 0.001043} = 0.357$

$$u_3 = 417.40 + 0.357(2505.6 - 417.40) = 1162.8874$$

$$\Delta u = 2728.90 - 1162.8874 = \boxed{1566 \frac{\text{kJ}}{\text{kg}}}$$

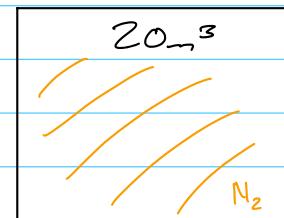


4. [Chapter 4] A 20 m^3 tank contains nitrogen (a near ideal gas) at 23°C and 600 kPa . Some nitrogen is allowed to escape until the pressure in the tank drops to 400 kPa . If the temperature at this point is 20°C , determine the amount of nitrogen that has escaped.



$$T_1 = 23^\circ\text{C} = 296\text{ K}$$

$$P_1 = 600\text{ kPa}$$



$$T_2 = 20^\circ\text{C} = 293\text{ K}$$

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

A-2 for
 C_P/C_V

Partial g.s const ($296 \approx 293 \approx 300$) : 0.2968 $\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

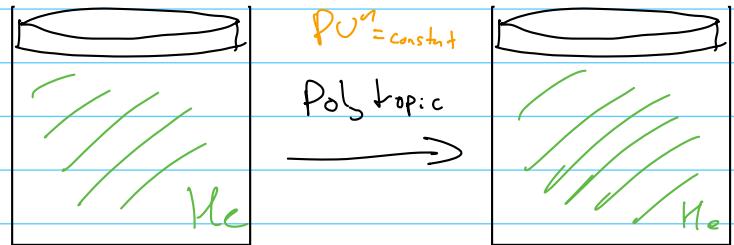
$$PV = mRT$$

$$m_1 = \frac{600\text{ kPa} (20 \times 1000)}{0.2968 (296)} = 136592\text{ kg}$$

$$m_2 = \frac{400 (20 \times 1000)}{0.2968 (293)} = 91493.78$$

$$(136592 - 91493) = \boxed{44.6\text{ kg}}$$

5. [Chapter 5] A piston-cylinder device contains helium gas initially at 150 kPa, 20°C, and 0.5 m³. The helium is now compressed in a polytropic process ($PV^n = \text{constant}$) to 400 kPa and 140°C. Determine the heat loss or gain during the process.



$$P_1 = 150 \text{ kPa}$$

$$T_1 = 20^\circ\text{C}$$

$$V_1 = 0.5 \text{ m}^3$$

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

$$T_2 = 140^\circ\text{C}$$

$$V_2 = 0.264 \text{ m}^3$$

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

$$V_2 = \frac{T_2 P_1 V_1}{T_1 P_2} = \frac{(140+273)(150 \text{ kPa})(0.5 \text{ m}^3)}{(20+273)(400 \text{ kPa})} = 0.264$$

1st Law: $Q_{in} - Q_{out} + W_{in} - W_{out} = \Delta U$, $\Delta U = mc_v \Delta T$

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

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

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

$$n = \frac{\ln\left(\frac{P_1}{P_2}\right)}{\ln\left(\frac{V_2}{V_1}\right)} = \frac{\ln\left(\frac{150}{400}\right)}{\ln\left(\frac{0.264}{0.5}\right)} = 1.536$$

Table A-2

$$R_{He} = 2.0769$$

$$c_v = 3.1156$$

$$PV = mRT$$

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

$$= 150(0.5)$$

$$2.0769(20+273)$$

$$= 0.123 \text{ kg}$$

$$Q_{in} + W_{in} = m c_v \Delta T$$

$$W_{piston} = \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{400(0.264) - 150(0.5)}{1-1.536}$$

$$Q_{in} = .123(3.1156)(120) - 57.089 \approx$$

$$Q_{in} = -11.10$$

$$W_{piston} = W_{in} = -57.089 \text{ J}$$

11.10 KJ Loss

2. Saturated H_2O @ $135^\circ C$, $x = 0.7$. Find Δ

From Table

$$P_{sat} = 313.22$$

$$V_f = 0.001075 \frac{m^3}{kg}$$

$$V_g = 0.58179 \frac{m^3}{kg}$$

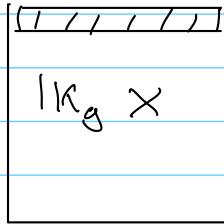
$$\Delta = \Delta_f + x(V_g - V_f)$$

$$= 0.001075 + 0.7(0.58179 - 0.001075)$$

$$= 0.4075755$$

$$\Delta \approx 0.408$$

3.

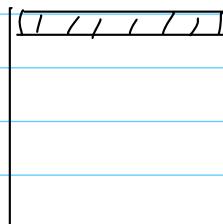


$$V_1 = 10 m^3$$

$$P_1 = 6 kPa$$

$$T_1 =$$

Polynomial
 $n = 1.5$



$$V_2 = 5 m^3$$

$$P_2 = 16.47 kPa$$

$$T_2 =$$

chemical x
 $C_v = 314 \frac{kJ}{kg \cdot K}$
 $m = 1 kg$

1st Law: $Q_{in} - Q_{out} + W_{in} - W_{out} = \Delta U$ Adiabatic = no heat transfer

$$\begin{aligned} P_1 V_1^n &= P_2 V_2^n \\ P_2 &= \frac{P_1 V_1^n}{V_2^n} \\ &= \frac{6 kPa (10)^{1.5}}{(5)^{1.5}} \\ &= 16.47 kPa \end{aligned}$$

$$\begin{aligned} W_{piston} &= \frac{P_2 V_2 - P_1 V_1}{1-n} \\ &= \frac{16.47(5) - 6(10)}{1-1.5} \\ &= -44.70 \text{ kJ} \end{aligned}$$

Drilled nozzle as work in!
 $W_{in} = 44.70 \text{ kJ}$

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

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

$$\frac{6 kPa (10)}{16.47 (5)} = \frac{T_1}{T_2}$$

$$0.707 = \frac{T_1}{T_2}$$

$$T_1 = T_2 0.707$$

$$\begin{aligned} W_{in} &= \Delta U, \quad \Delta U = m C_v \Delta T \\ W_{in} &= m C_v (\Delta T) \end{aligned}$$

$$44.70 \text{ kJ} = 1 \text{ kg} (314 \frac{kJ}{kg \cdot K}) (\Delta T)$$

$$\rightarrow \Delta T = 13.828^\circ K$$

$$T_2 - T_1 = 13.828^\circ K$$

$$T_2 - T_1 0.707 = 13.828^\circ K$$

$$T_2 (1 - 0.707) = 13.828^\circ K$$

$$T_2 = -218.98$$

ECHE225 HW3

1. [Chapter 6] Water enters the constant 150-mm inside diameter tubes of a boiler at 5 MPa and 60°C and leaves the tubes at 4 MPa and 400°C with a velocity of 75 m/s. Calculate the velocity of the water at the tube inlet and the inlet volumetric flow rate.

$$\dot{m} = PV_{\text{Avg}}A_c$$

$$\dot{V} = \frac{\dot{m}}{P} = V_{\text{Avg}}A_c$$

Compressed Liquid

$$\gamma = 0.0010149$$

$$\rho = 985.319$$

Superheated Vapour

$$\gamma = 0.07343$$

$$\rho = 13.618$$

Assume normal, steady flow. Constant Diameter and $\dot{m}_1 = \dot{m}_2$

$$\frac{\dot{m}}{A_c} = \rho V_{\text{Avg}} \rightarrow \rho_1 V_{\text{Avg}} = \rho_2 V_{\text{Avg}_2}$$

$$\Rightarrow V_{\text{Avg}_1} = \frac{\rho_2 V_{\text{Avg}_2}}{\rho_1} = \frac{13.618(75)}{985.319} = 1.04 \frac{m}{s}$$

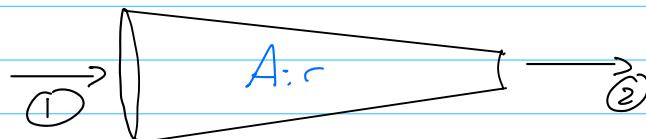
$$A_c = \pi r^2 = \pi \left(\frac{0.15}{2}\right)^2 = 0.0176 \text{ m}^2$$

(Diameter given)

$$\dot{V}_1 = V_{\text{Avg}_1} A_c = 1.04 (0.0176) = 0.0184 \frac{m^3}{s}$$

$$V'_1 = 1.04 \frac{m}{s}, \dot{V}_1 = 0.0184 \frac{m^3}{s}$$

2. [Chapter 6] Air at 600 kPa and 500 K enters an adiabatic nozzle that has an inlet-to-exit ratio of 2:1 with a velocity of 100 m/s and leaves with a velocity of 400 m/s. Determine:
 (a) the exit temperature and (b) the exit pressure of the air. [Assume ideal gas behavior and use c_p at 500 K]



$$\frac{\text{inlet}}{\text{outlet}} = \frac{2}{1}$$

$$P_1 = 600 \text{ kPa} = 0.6 \text{ MPa}$$

$$P_2 =$$

$$\frac{c_p @ 500 \text{ K}}{1.029 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}}$$

$$T_1 = 500 \text{ K}$$

$$T_2 =$$

$$V_1 = 100 \text{ m/s}$$

$$V_2 = 400 \text{ m/s}$$

Assume Ideal Behavior
 $\Delta h = \int_1^2 c_p dT$

a) 1st Law: $\dot{m} [(h_2 - h_1) + \frac{1}{2}(V_2^2 - V_1^2)]$

$$-(h_2 - h_1) = \frac{1}{2}(V_2^2 - V_1^2)$$

$$\Delta h = -\frac{1}{2}(400^2 - 100^2)$$

$$\Delta h = -75,000 \frac{\text{J}}{\text{kg}} = -75 \frac{\text{kJ}}{\text{kg}}$$

Ide. $\Rightarrow -75 = c_p \Delta T$

$$-75 = 1.029(T_2 - T_1)$$

$$T_2 = 427.114 \text{ K}$$

$$T_2 = \frac{-75}{1.029} + 500 = 427.114 \text{ K}$$

b) Use 1st Law: $PV = mRT$

$$P = \rho RT$$

$$P_1 = \frac{P_1}{RT_1} \text{ and } P_2 = \frac{P_2}{RT_2}$$

Mass is constant: $\dot{m}_1 = \dot{m}_2$

$$\rho_1 r_1 A_1 = \rho_2 r_2 A_2$$

$$\frac{A_1}{A_2} = \frac{2}{1}$$

$$\rho_1 r_1^2 A_2 = \rho_2 r_2^2 A_1$$

$$A_1 = 2A_2$$

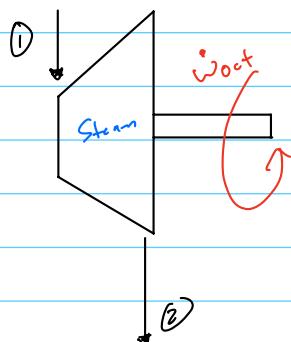
$$2 \frac{P_1}{RT_1} r_1 = \frac{P_2}{RT_2} r_2$$

$$\frac{2T_2 P_1 r_1}{T_1 r_2} = P_2$$

$$P_2 = \frac{2(427.114)(600)(100)}{500(400)}$$

$$P_2 = 256.268 \text{ kPa}$$

3. [Chapter 6] Steam enters an adiabatic turbine at 8 MPa and 400°C and leaves at 100 kPa with a quality of 90%. Neglecting the changes in potential and kinetic energies, determine the mass flow rate required for a power output of 5 MW.



$$P_1 = 8 \text{ MPa} \quad T_1 = 400^\circ\text{C} \quad \xrightarrow{\text{SH}} h_1 = 3139.40 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{W}_{\text{out}} = \dot{m} \text{MW}$$

$$P_2 = 100 \text{ kPa} \quad x = 0.90 \quad \xrightarrow{\text{Sct. M.W.}} h_f = 417.51 \frac{\text{kJ}}{\text{kg}}$$

$$h_g = 2675 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_f + x(h_g - h_f)$$

$$= 417.51 + 0.90(2675 - 417.51)$$

$$= 2449.25 \frac{\text{kJ}}{\text{kg}}$$

$$\begin{aligned} \text{1st Law: } \dot{W}_{\text{out}} &= \dot{m}(h_2 - h_1) \\ -\dot{W}_{\text{out}} &= \dot{m}(h_1 - h_2) \\ -\text{SMW} &= \dot{m}(2449.25 - 3139.40) \end{aligned}$$

Commercial Unit Block: $\text{SMW} \times \frac{1000000 \text{ W}}{1 \text{ MW}} = 5,000,000 \frac{\text{J}}{\text{s}}$ \\$w\}

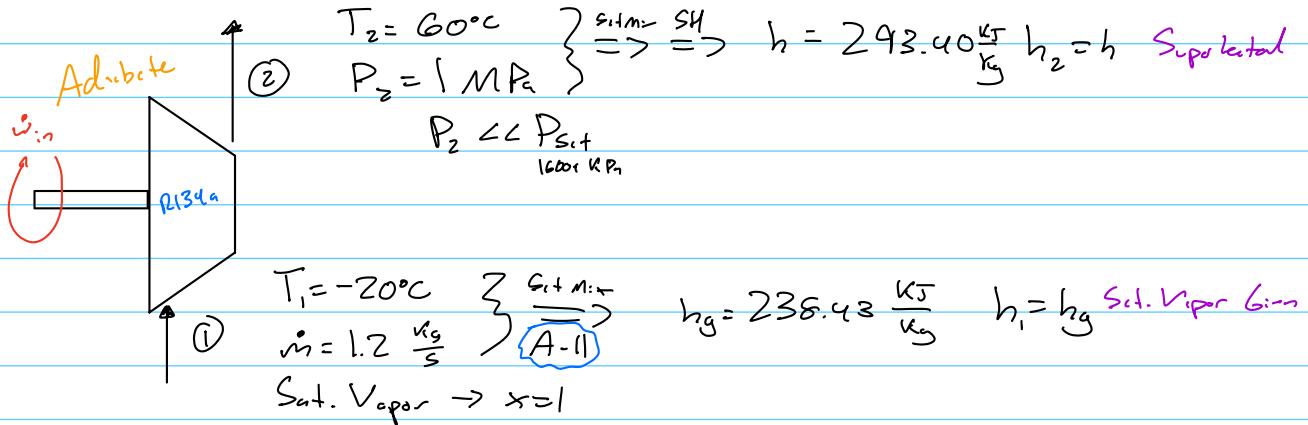
$$= 5,000 \frac{\text{kW}}{\text{s}}$$

$$\begin{aligned} -5,000 \frac{\text{kW}}{\text{s}} &= \dot{m}(-690.149 \frac{\text{kJ}}{\text{kg}}) \\ \Rightarrow \dot{m} &= 7.245 \frac{\text{kg}}{\text{s}} \end{aligned}$$

$$\boxed{\dot{m} = 7.245 \frac{\text{kg}}{\text{s}}}$$

Easy Q. Just intro to R-134a Tables !!

4. [Chapter 6] Refrigerant R134a enters an adiabatic compressor as saturated vapor at -20°C and leaves at 1 MPa and 60°C. The mass flow rate of the refrigerant is 1.2 kg/s. Determine (a) the power input to the compressor and (b) the volumetric flow rate of the refrigerant at the compressor inlet.



a) 1st Law: $\dot{W}_{\text{net}} = m(h_2 - h_1)$

$\rightarrow \dot{W}_{\text{net}} = m(h_2 - h_g)$

$\dot{W}_{\text{net}} = 1.2 \frac{\text{kg}}{\text{s}} (293.40 - 238.43) \frac{\text{kJ}}{\text{kg}}$

$\dot{W}_{\text{net}} = 65.964 \frac{\text{kJ}}{\text{s}}$

{ KW }

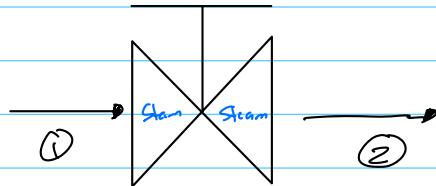
b) $\dot{V} = \frac{\dot{m}}{P} \quad P? \xrightarrow{\text{Saturated}} \quad \dot{V}_g = 0.1473 \text{ m}^3/\text{s}$

$P = \frac{1}{\dot{V}} = 6.787 \frac{\text{kg}}{\text{m}^3}$

$\dot{V} = \frac{1.2 \frac{\text{kg}}{\text{s}}}{6.787 \frac{\text{kg}}{\text{m}^3}} = 0.172 \text{ m}^3/\text{s}$

$\dot{V} = 0.172 \frac{\text{m}^3}{\text{s}}$

5. [Chapter 6] A well-insulated valve is used to throttle steam from 5 MPa and 400°C to 1 MPa. Determine the final temperature of the steam.



$$\textcircled{1} \text{ Steam table } \xrightarrow{\text{Sat}} h = 3196.70 \frac{\text{kJ}}{\text{kg}}$$

$$P_1 = 5 \text{ MPa} \quad P_2 = 1 \text{ MPa}$$

$$T_1 = 400^\circ\text{C} \quad T_2 = ?$$

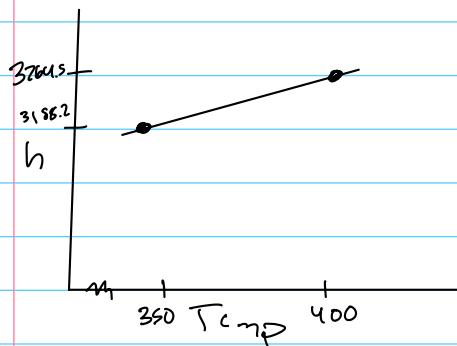
1st Law: $h_1 = h_2$

$$3196.70 \frac{\text{kJ}}{\text{kg}} = h_2$$

Our h_2 lies between...

$$P_2 = 1 \text{ MPa} = 1000 \text{ kPa} \quad \left. \begin{array}{l} \xrightarrow{\text{Steam}} T_a = 350 \rightarrow 3156.20 \\ \xrightarrow{\text{Tables}} T_b = 400 \rightarrow 3264.50 \end{array} \right\} \frac{\text{kJ}}{\text{kg}}$$

Basic inaccurate Intep: $\frac{3264.50 - 3156.20}{400 - 350} = 2.126 \frac{\text{kJ}}{\text{kg}\text{C}}$



$$\frac{3264.50 - 3196.70}{400 - T_2} = 2.126$$

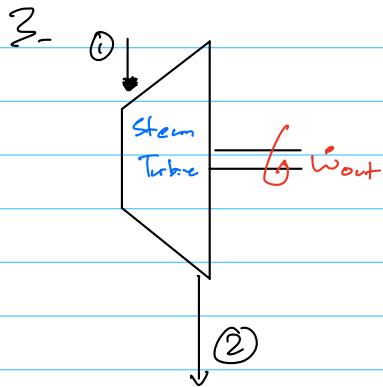
$$67.8 = 2.126(400 - T_2)$$

$$31.841 = 400 - T_2$$

$$T_2 \approx 368.109^\circ\text{C}$$

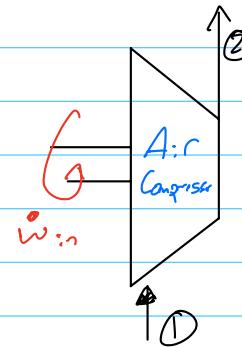
Trevor Swan

ECHE225: QUIZ #3 // 9.19.24



$$\begin{aligned} P_1 &= 12.5 \text{ MPa} \\ T_1 &= 500^\circ\text{C} \\ \dot{m} &= 25 \text{ kg/s} \end{aligned}$$

$$\begin{aligned} P_2 &= 10 \text{ kPa} \\ X &= 0.92 \end{aligned}$$



$$\begin{aligned} P_2 &= 1 \text{ MPa} \\ T_2 &= 620\text{K} \\ C_p &= 1.0303 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \end{aligned}$$

$$\begin{aligned} P_1 &= 98 \text{ kPa} \\ T_1 &= 295\text{K} \\ \dot{m}_1 &= 10 \text{ kg/s} \end{aligned}$$

a) Work done \dot{W}_{out} by Turbine to 1000°C [mw]

$$1^{\text{st}} \text{ Law: } \dot{W}_{in} - \dot{W}_{out} = \dot{m}(h_2 - h_1)$$

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

$$h_1 \xrightarrow[\text{Table}]{\text{SI}} h_1 = 3343.6 \frac{\text{kJ}}{\text{kg}}$$

$$\begin{aligned} h_2 \xrightarrow[\text{Table}]{\text{Sat. Mix}} h_f &= 141.81 \frac{\text{kJ}}{\text{kg}} \\ h_g &= 2583.90 \frac{\text{kJ}}{\text{kg}} \end{aligned} \quad h_2 = 141.81 + 0.92(2583.90 - 141.81) = 2392.533$$

$$\dot{W}_{out} = 25 \frac{\text{kg}}{\text{s}} (3343.6 - 2392.533) \frac{\text{kJ}}{\text{kg}} = 23776.675 \text{ kW}$$

$$23776.675 \text{ kW} = \boxed{23777 \text{ mw}}$$

b) Work done \dot{W}_{in} Compressor to 100°C (kw)

$$1^{\text{st}} \text{ Law: } \dot{W}_{in} - \dot{W}_{out} = \dot{m}(h_2 - h_1)$$

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

Assume air is ideal

$$\Delta h = C_p \Delta T \Rightarrow h_2 - h_1 = C_p(T_2 - T_1)$$

$$\begin{aligned} &= 1.0303 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} (620\text{K} - 295\text{K}) \\ &= 334.85 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

$$\Rightarrow \dot{W}_{in} = 10 \frac{\text{kg}}{\text{s}} (334.85 \frac{\text{kJ}}{\text{kg}}) = \boxed{3348.5 \text{ kW}} \quad (3348.5 \text{ mw})$$

c) Turbine Produces 23.777 mw

- Compressor Consumes 3.3485 mw

20.4285 mw delivered to generator

The \downarrow Turbine power both!

Net power $\rightarrow 100^\circ\text{ms}: \boxed{20.43 \text{ mw}}$

ECHE225 HW4

1. [Chapter 7] An automobile engine consumes fuel at a rate of 22 L/hr and delivers 50 kW of power to the wheels. If the fuel has a heating value of 44,000 kJ/kg and a density of 2 g/cm³, determine the efficiency of this engine.

$$\dot{V} = 22 \frac{\text{L}}{\text{hr}} ; \eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}} ; \dot{W}_{out} = \dot{W}$$

$$\dot{m} = 22 \frac{\text{L}}{\text{hr}} \times \frac{1000 \frac{\text{cm}^3}{\text{L}}}{1 \text{L}} \times \frac{2 \frac{\text{g}}{\text{cm}^3}}{\cancel{1 \text{cm}^3}} \times \frac{1 \text{kg}}{1000 \cancel{\text{g}}} = 44 \frac{\text{kg}}{\text{hr}}$$

$$\dot{Q}_{in} = 44 \frac{\text{kg}}{\text{hr}} \times 44,000 \frac{\text{kJ}}{\text{kg}} \times \frac{1 \text{hr}}{60 \text{min}} \times \frac{1 \text{min}}{60 \text{sec.}} = 537.778 \text{ kW}$$

$$\eta_{th} = \frac{50 \text{ kW}}{537.778 \text{ kW}} = 0.0929 \rightarrow \boxed{\eta_{th} = 9.29\%}$$

2. [Chapter 7] Determine the COP of a refrigerator that removes heat from the food compartment at a rate of 5100 kJ/hr for each kW of power it consumes. Also determine the rate of heat rejection to the outside air.

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L} , \quad \text{Find: } COP_R, \dot{Q}_H$$

$$\dot{Q}_L = 5100 \frac{\text{kJ}}{\text{hr}} \times \frac{1\text{hr}}{3600 \text{ sec}} = 1.4167 \text{ kW}$$

$$\dot{W}_{in} = 1 \text{ kW} ; \quad COP_R = \frac{1.4167 \text{ kW}}{1 \text{ kW}} \rightarrow COP_R = 1.4167$$

$$COP_R = \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L} \quad \dot{Q}_H = \frac{1.4167 \text{ kW}}{1.4167} + 1.4167 = 2.4167 \text{ kW}$$

$$(\dot{Q}_H - \dot{Q}_L), COP_R = \dot{Q}_L$$

$$\dot{Q}_H = \frac{\dot{Q}_L}{COP_R} + \dot{Q}_L$$

Given \dot{Q}_L in $\frac{\text{kJ}}{\text{hr}}$, let's convert back!

$$\dot{Q}_H = 2.4167 \frac{\text{kJ}}{\text{s}} \times \frac{3600 \text{ s}}{1 \text{ hr}} = 8700 \frac{\text{kJ}}{\text{hr}}$$

$$\dot{Q}_H = 8700 \frac{\text{kJ}}{\text{hr}}$$

COP_{12} comes from 1st law: $\dot{W}_{in} = \dot{Q}_H - \dot{Q}_L$

3. [Chapter 7] Determine the COP of a heat pump that supplies energy to a house at a rate of 6500 kJ/hr for each kW of electric power it draws. Also determine the rate of energy absorption from the outside air.

$$COP_{HP} = \frac{\dot{Q}_u}{\dot{W}_{in}} = \frac{\dot{Q}_u}{\dot{W}_{in}} = \frac{\dot{Q}_u}{\dot{Q}_u - \dot{Q}_v}, \dot{W}_{in} = 1 \text{ kW}; \text{ Find } COP_{HP}, \dot{Q}_v$$

$$\dot{Q}_u = 6500 \frac{\text{kJ}}{\text{hr}} \times \frac{1 \text{ hr}}{3600 \text{ sec}} = 1.806 \text{ kW}$$

$$COP_{HP} = \frac{1.806 \text{ kW}}{1 \text{ kW}} = 1.806 \rightarrow COP_{HP} = 1.806$$

$$COP_{HP} = \frac{\dot{Q}_u}{\dot{Q}_u - \dot{Q}_v}$$

$$\dot{Q}_v = 6500 \frac{\text{kJ}}{\text{hr}} - \frac{6500 \text{ kJ/hr}}{1.806} = 2900 \frac{\text{kJ}}{\text{hr}}$$

$$\dot{Q}_u - \dot{Q}_v = \frac{\dot{Q}_u}{COP_{HP}}$$

$$\dot{Q}_v = \dot{Q}_u - \frac{\dot{Q}_u}{COP_{HP}}$$

COP_{HP} is just a ratio,
so you can convert with $\frac{\text{kJ}}{\text{hr}}$
values (not limited to kW units)

COP_{HP} comes from 1st Law: $\dot{W}_{in} = \dot{Q}_u - \dot{Q}_v$

4. [Chapter 7] A Carnot heat engine receives 600 kJ of heat from a source of unknown temperature and rejects 175 kJ of it to a sink at 20°C. Determine (a) the temperature of the source and (b) the thermal efficiency of the heat engine.

For a Carnot Heat Engine

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

Generally:

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

a) $T_L = 20^\circ\text{C}$, $Q_L = 175 \text{ kJ}$, $Q_H = 600 \text{ kJ}$, find T_H

$$T_L = 20^\circ\text{C} = 293.15 \text{ K}$$

$$\eta_{th, \text{Carnot}} = \eta_{th}$$

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

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

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

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

$$= \underline{600 \text{ kJ} \cdot (293.15 \text{ K})}$$

$$= \underline{175 \text{ kJ}}$$

$$= 1005.09 \text{ K}$$

$$T_H = 1005.09 \text{ K}$$

Must use Kelvin to find

absolute temperature \rightarrow avoids negative temperatures!

b) $\eta_{th, \text{Carnot}} = 1 - \frac{T_L}{T_H}$

$$= 1 - \frac{293.15 \text{ K}}{1005.09 \text{ K}}$$

$$= 0.7083$$

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

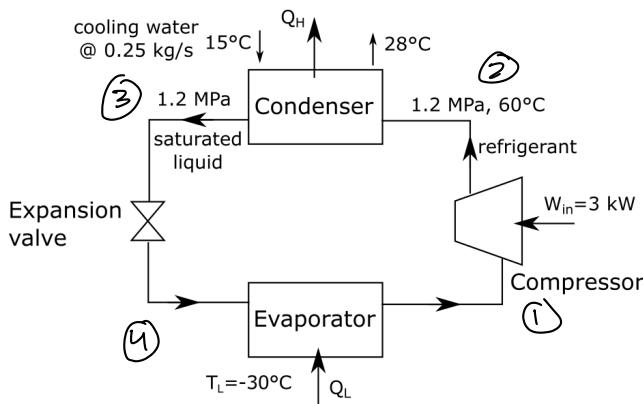
$$= 1 - \frac{175 \text{ kJ}}{600 \text{ kJ}}$$

$$\eta_{th} = 70.83\%$$

Values obviously agree!

5. [Chapter 7] A commercial refrigerator with R134a as the working fluid is used to keep the refrigerated space at -30°C by rejecting waste heat to cooling water that enters the condenser at 15°C at a rate of 0.25 kg/s and leaves at 28°C . The refrigerant enters the condenser at 1.2 MPa and 60°C and leaves at the same pressure as a saturated liquid. If the compressor consumes 3 kW of power, determine:

- the mass flow rate of the refrigerant
- the refrigeration load
- the COP
- the minimum power input to the compressor for the same refrigeration load.



$$\text{Water @ } 25-50^{\circ}\text{C} : c_p = 4.18 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$T_{\text{byle}} : \textcircled{2} \left. \begin{array}{l} 1.2 \text{ MPa} \\ 60^{\circ}\text{C} \end{array} \right\} \xrightarrow{\text{SH}} h_2 = 289.66$$

$$\textcircled{3} \left. \begin{array}{l} 1.2 \text{ MPa} \\ \text{Sat Liquid} \end{array} \right\} h_3 = 117.29$$

$$\text{a) 1st Law: } W_{in} = Q_H - Q_L$$

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

$$\text{1st Law: } \textcircled{1} \left. \begin{array}{l} \text{Condenser} \\ \text{condenser} \end{array} \right\} Q_{out} = m(h_3 - h_2)$$

$$(1) \left. \begin{array}{l} \text{Condenser} \\ \text{Condenser} \end{array} \right\} Q_{out} = m(h_2 - h_3)$$

open system

in - out

$$13.585 \text{ kW} = m(289.66 - 117.29)$$

$$13.585 \text{ kW} = m(171.87)$$

$$\text{For water in condenser: } \textcircled{2} \left. \begin{array}{l} \text{Condenser} \\ \text{Condenser} \end{array} \right\} Q_{out} = m \cdot c_p (T_3 - T_2)$$

$$m = 0.079 \frac{\text{kg}}{\text{s}}$$

$$= 25 \frac{\text{kg}}{\text{s}} \cdot 4.18 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} (28 - 15)$$

$$= 13.585 \text{ kW}$$

b) Refrigeration Load = Heat Removal of evaporator = condenser heat rejected - work in

$$\text{Load: } \dot{Q}_{in} = \dot{Q}_{out} - W_{in} = 13.6 \text{ kW} - 3 \text{ kW} = 10.6 \text{ kW} \rightarrow \boxed{\text{Load: } 10.6 \text{ kW}}$$

$$\text{c) } CoP_D = \frac{\dot{Q}_{in}}{W_{in}} = \frac{10.6 \text{ kW}}{3 \text{ kW}}$$

$$\rightarrow \boxed{CoP_D = 3.533}$$

d) Looking for min work, turns to ideal/carnot cycle

$$COP_R = \frac{1}{\frac{T_H}{T_L} - 1} \rightarrow T_L = -30^\circ C = 243.15 K, T_H = 18^\circ C = 288.15 K$$

$$COP_{R2} = \frac{\dot{Q}_{in}}{\dot{w}_{in}} \rightarrow \dot{w}_{in} = \frac{\dot{Q}_{in}}{COP_R}, \dot{Q}_{in} = 10.6 \text{ kW}$$

$$\begin{aligned}\dot{w}_{in} &= \frac{\dot{Q}_{in}}{\frac{1}{\frac{T_H}{T_L} - 1}} = \left(\frac{T_H}{T_L} - 1 \right) \dot{Q}_{in} \\ &= \left(\frac{288.15 K}{243.15 K} - 1 \right) 10.6 = 1.96 \text{ kW}\end{aligned}$$

$$\boxed{\dot{w}_{in,min} = 1.96 \text{ kW}}$$

1. Efficiency of irreversible always less than in reversible cycle

2. Ideal HP Given

$$\text{CoP}_{\text{HP}} = \frac{Q_{\text{out}}}{W_{\text{in}}} = \frac{1}{1 - \frac{Q_L}{Q_H}} \quad \left. \begin{array}{l} \\ \end{array} \right\} \text{Generally}$$

$$\text{CoP}_{\text{HP}} = 1.9$$

$$T_L = 290\text{K} \quad \text{air}$$

$$\text{CoP}_{\text{HP}} = \frac{1}{1 - \frac{T_L}{T_H}} \quad \left. \begin{array}{l} \text{Ideal/constant} \\ \end{array} \right.$$

Find T_H

$$\text{CoP}_{\text{HP}} \left(1 - \frac{T_L}{T_H} \right) = 1$$

$$T_H = \frac{T_L}{1 - \frac{1}{\text{CoP}_{\text{HP}}}}$$

$$1 - \frac{T_L}{T_H} = \frac{1}{\text{CoP}_{\text{HP}}} = \frac{290\text{K}}{1 - \frac{1}{1.9}} = 612\text{K}$$

$$\frac{T_L}{T_H} = 1 - \frac{1}{\text{CoP}_{\text{HP}}}$$

$$T_H = 612\text{K}$$

3. Carnot Heat Engine

$$\eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} = 0.60$$

Generally

$$\eta_{\text{Carnot}} = \frac{W_{\text{out}}}{Q_H} \rightarrow W_{\text{out}} = \eta_{\text{Carnot}} \cdot Q_H$$

\uparrow
 $Q_H = \dot{Q}_{\text{in}}$

1st Law: $\dot{Q}_{\text{in}} = m(h_m - h_i)$

$$\dot{Q}_{\text{in}} = m \times c_p \times (T_{\text{in}} - T_{\text{out}})$$

$T_{\text{in}} = T_H \quad T_{\text{out}} = T_L$

$$1 - \frac{T_L}{T_H} = 0.60$$

$$\dot{Q}_{\text{in}} = m \times c_p \times (T_H - T_L)$$

$$= 0.05 \frac{\text{kg}}{\text{s}} \times 4.18 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \times (500\text{K} - 200\text{K})$$

$$1 - \frac{T_L}{500} = 0.60$$

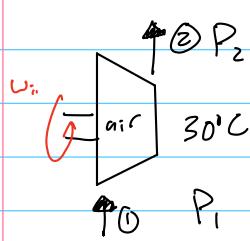
$$\rightarrow T_L = 200$$

$$\dot{Q}_{\text{in}} = 62.7 \text{ kW} \rightarrow \dot{Q}_{\text{out}} = 0.60 \cdot 62.7 \text{ kW} = 37.62$$

$$\dot{W}_{\text{out}} = 37.62 \text{ kW}$$

ECHE225 HW5

1. [Chapter 8] Air is compressed by a 20 kW compressor from P₁ to P₂. The air temperature is maintained constant at 30°C. Determine the rate of entropy change in the air. State the assumptions made in solving this problem.



$$1^{\text{st}} \text{ Law: } \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \dot{m}(\dot{U}_{in} - \dot{U}_{out})$$

$$\dot{Q}_2 = -\dot{W}_{in} = -20 \text{ kW}$$

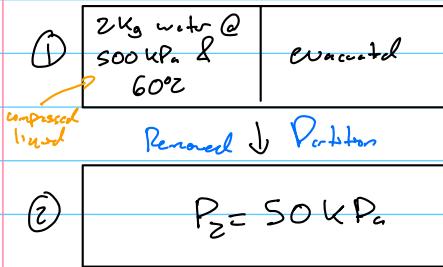
$$\dot{s} = \frac{-\dot{W}_{in}}{T_0} ?$$

$$\Delta s_{\text{sur}} = \frac{\dot{Q}_2}{T_0} = \frac{-20 \text{ kW}}{30 + 273.15 \text{ K}} = -0.066 \frac{\text{kW}}{\text{K}}$$

$$\boxed{\Delta s_{\text{sur}} = -0.066 \frac{\text{kW}}{\text{K}}}$$

Assumptions: Compressor is ideal, process is isothermal, surroundings infinite, specific heat constant

- ~~2~~ 2. [Chapter 8] A rigid tank is divided into two equal parts by a partition. One part of the tank contains 2 kg of compressed liquid water at 500 kPa and 60°C while the other part is evacuated. The partition is now removed and the water expands to fill the entire tank. Determine the entropy change of water during the process if the final pressure in the tank is 50 kPa.



$$\Delta S = m(s_2 - s_1)$$

$$J_2 = 2 \cdot J_1$$

$$J_2 = J_f + x_2(J_g - J_f)$$

$$s_2 = s_f + x_2(s_g - s_f)$$

$$\Delta S = 0.524 \frac{\text{kJ}}{\text{K}}$$

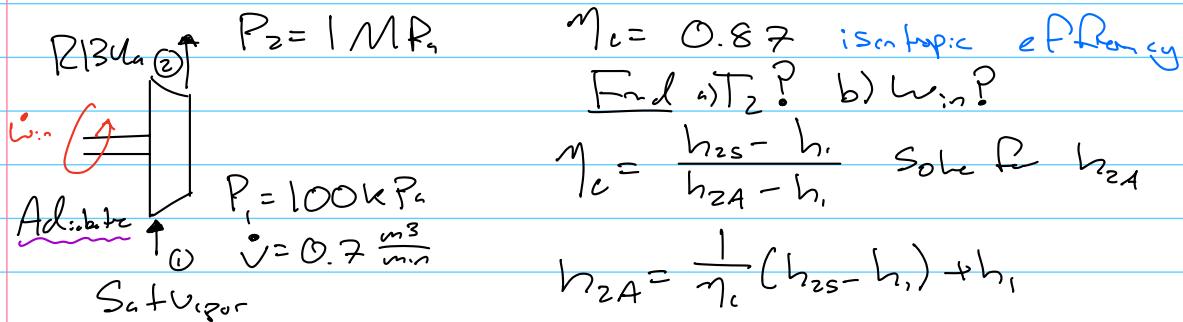
$$T_1 = 60^\circ\text{C} \xrightarrow[\text{water}]{s_f +} \left\{ \begin{array}{l} J_1 = 0.001017 \\ s_1 = 0.8313 \end{array} \right. \quad \left\{ \begin{array}{l} \sum \frac{m^3}{kg} \\ \sum \frac{kJ}{kg \cdot K} \end{array} \right. \quad J_2 = 0.002034$$

$$P_2 = 50 \text{ kPa} \xrightarrow[\text{water}]{s_f +} \left\{ \begin{array}{l} J_f = 0.001030 \\ J_g = 3.2403 \\ s_f = 1.0912 \\ s_g = 7.5931 \end{array} \right. \quad \left\{ \begin{array}{l} \sum \frac{m^3}{kg} \\ \sum \frac{kJ}{kg \cdot K} \end{array} \right. \quad \begin{aligned} x_2 &= \frac{0.002034 - 0.001030}{3.2403 - 0.001030} \\ x_2 &= 0.0003099 \end{aligned}$$

$$\Rightarrow s_2 = 1.0912 + 0.0003099(7.5931 - 1.0912) = 1.6932$$

$$\Delta S = 2(1.6932 - 0.8313) = 0.5238 \frac{\text{kJ}}{\text{K}}$$

3. [Chapter 8] R134a enters an adiabatic compressor as saturated vapor at 100 kPa at a rate of $0.7 \text{ m}^3/\text{min}$ and exits at 1 MPa. If the isentropic efficiency of the compressor is 87 percent, determine (a) the temperature of the refrigerant at the exit of the compressor and (b) the power input, in kW.



State ①

$$P_1 = 100 \text{ kPa} \quad \left. \begin{array}{l} \xrightarrow{\text{S}_1} \\ \xrightarrow{\text{Vapor}} \end{array} \right. \begin{array}{l} T_1 = -26.37^\circ\text{C} \\ h_g = h_i = 234.46 \frac{\text{kJ}}{\text{kg}} \end{array} \quad \begin{array}{l} S_g = S_i = 0.95191 \frac{\text{kJ}}{\text{kg K}} \\ \dot{V}_g = 0.19255 \frac{\text{m}^3}{\text{kg}} \end{array}$$

State ②

$$P_2 = 1 \text{ MPa} \quad \left. \begin{array}{l} \xrightarrow{\text{S}_2} \\ \xrightarrow{\text{min}} \end{array} \right. S_f < S_g < S_2 \quad \left. \begin{array}{l} \xrightarrow{\text{S}_2} \\ \xrightarrow{\text{h}_{2s}} \end{array} \right. h_{2s} = 282.76 \quad \text{Locally}$$

Find turbine on the steam tables

$$h_{2A} = \frac{1}{0.87} (282.76 - 234.46) + 234.46 = 289.977$$

a) $P_2 = 1 \text{ MPa}$ $\left. \begin{array}{l} \xrightarrow{\text{S}_2} \\ \xrightarrow{\text{min}} \end{array} \right. h_f < h_g < h_{2A} \quad \left. \begin{array}{l} \xrightarrow{\text{S}_2} \\ \xrightarrow{\text{h}_{2A}} \end{array} \right. \begin{array}{l} h_{500} = 282.76 \\ h_{600} = 293.40 \end{array}$

Interpolate: $\frac{293.40 - 282.76}{60 - 50} = 1.064 \frac{\text{kJ}}{\text{kg C}}$

$$\bar{T}_2 = 50^\circ + \frac{289.977 - 282.76}{1.064} = 56.78^\circ\text{C}$$

$$T_{2A} = 56.78^\circ\text{C}$$

b) $\dot{m} = 0.7 \frac{\text{m}^3}{\text{min}} \cdot \frac{1}{0.19255} \frac{\text{kg}}{\text{m}^3} = 3.6354 \frac{\text{kg}}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.0606$

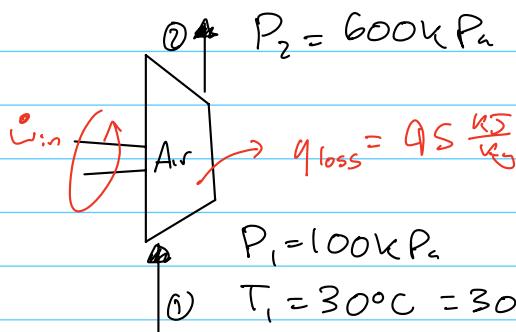
$$\dot{W}_{comp} = \dot{m} (h_{2A} - h_i) = 0.0606 \frac{\text{kg}}{\text{sec}} (289.977 - 234.46 \frac{\text{kJ}}{\text{kg}})$$

$$= 3.36 \text{ kW}$$

$$\dot{W}_{pump} = 3.36 \text{ kW}$$

4. [Chapter 8] Air enters a compressor steadily at ambient conditions of 100 kPa and 30°C and leaves at 600 kPa. Heat is lost from the compressor in the amount of 95 kJ/kg and the air experiences an entropy decrease of 0.30 kJ/kgK. Using constant specific heats, determine:

- the exit temperature of the air
- the work input to the compressor (in kJ/kg)
- the total entropy change during the process (in kJ/kgK)



Air @ 300K

$$\begin{cases} c_p = 1.005 \frac{\text{kJ}}{\text{kg}\text{K}} \\ c_v = 0.716 \frac{\text{kJ}}{\text{kg}\text{K}} \end{cases} \Rightarrow \kappa = 1.400$$
 $R = 0.2870$

$R = c_p - c_v$
from defn

$Q_{in} - Q_{out} + W_{in} - W_{out} = m(h_2 - h_1)$

$W_{in} - Q_{out} = m(h_2 - h_1)$

$W_{in} - q_{loss} = c_p(T_2 - T_1)$

Use enthalpy form

a) $\Delta s_{sys} = c_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right)$

 $- 0.30 \frac{\text{kJ}}{\text{kg}\text{K}} = 1.005 \ln \left(\frac{373.15}{303.15} \right) - 0.2870 \ln \left(\frac{600}{100} \right) \rightarrow T_2 = 373.15 \text{ K}$

$$T_2 = 102.03^\circ\text{C}$$

b) $W_{in} = q_{loss} + c_p(T_2 - T_1) = 95 + 1.005(102.03 - 30) = 167.39$

$$W_{in} = 167.39$$

c) $\Delta s_{surr} = \frac{Q}{T_0} = \frac{q_{loss}}{T_1} = + \frac{95 \frac{\text{kJ}}{\text{kg}}} {303.15 \text{ K}} = 0.3134 \frac{\text{kJ}}{\text{kg}\text{K}}$

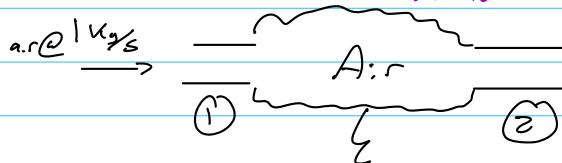
pos w/
respect to
surrounds

$$\Delta s_{total} = \Delta s_{sys} + \Delta s_{surr} = -0.30 + 0.3134 = 0.0134$$

$$\Delta s_{total} = 0.0134 \frac{\text{kJ}}{\text{kg}\text{K}}$$

5. An inventor claims to have invented an adiabatic steady-flow device with a single inlet and single outlet that produces 230 kW when expanding 1 kg/s of air from 1200 kPa and 300°C to 100 kPa. Is the claim valid?

We are looking to see if $\Delta s_{tot} < 0$ (impossible)



Assume ideal and

$$-\dot{w}_{out} = \dot{m} c_p (T_2 - T_1)$$

$$\begin{aligned} P_1 &= 1200 \text{ kPa} & P_2 &= 100 \text{ kPa} & 600 \text{ kJ} \\ T_1 &= 300^\circ\text{C} & \dot{w}_{out} &= 230 \text{ kW} & a.r \\ T_2 &= 81.161^\circ\text{C} & & & c_v = 0.764 \Rightarrow \kappa = 1.326 \\ & & & & c_p = 1.081 \Rightarrow R = 0.287 \end{aligned}$$

$$\Delta s_{sur} = 0 \text{ as system is adiabatic}$$

$$T_2 = \frac{-\dot{w}_{out}}{\dot{m} c_p} + T_1 = 354.31$$

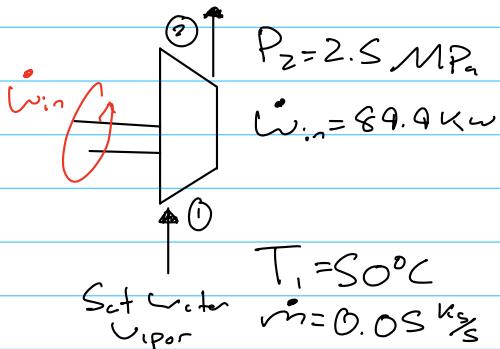
$$\Delta s_{sys} = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$= 1.081 \ln\left(\frac{354.31}{523.15}\right) - 0.287 \ln\left(\frac{100}{1200}\right) = 0.208$$

$$\Delta s_{sys} = \Delta s_{tot} = 0.207$$

Possible

3-6) Adiabatic Compressor

3) Find Outlet $^\circ\text{C}$ T_2

$$\begin{aligned} T_1 &= 50^\circ\text{C} \\ S_{in} + U_{ipar} &\xrightarrow[S_{out}]{h_g = h_i} h_g = h_i = 2591.3 \\ S_g &= S_i = 8.0748 \end{aligned}$$

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

$$\begin{aligned} h_2 &= \frac{\dot{W}_{in}}{m} + h_1 = \frac{89.9 \text{ kW}}{0.05 \frac{\text{kg}}{\text{s}}} + 2591.30 \\ h_2 &= 4389.30 \frac{\text{kJ}}{\text{kg}} \end{aligned}$$

$$\left. \begin{array}{l} P_2 = 2.5 \text{ MPa} \\ h_2 = 4389.30 \end{array} \right\} \Rightarrow h_2 < h_g < h_{2s} \quad \left. \begin{array}{l} h_2 < h_g \\ h_g < h_{2s} \end{array} \right\} \Rightarrow T_2 = 900^\circ\text{C} \quad \boxed{T_2 = 900^\circ\text{C}}$$

Exact match @ $P = 2.5 \text{ MPa}$, no interpolation

4) Phase change fluid: isentropic $\rightarrow S_1 = S_2$

$$\left. \begin{array}{l} T_1 = 50^\circ\text{C} \\ S_{in} + U_{ipar} \end{array} \right\} S_1 = 8.0748 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \quad \boxed{S_2 = 8.0748 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}}$$

5) Entropy = $4149.2 \frac{\text{kJ}}{\text{kg}}$? Enthalpies in units $\frac{\text{kJ}}{\text{kg}}$, will assume enthalpy

$$\begin{aligned} \dot{W}_{ideal} &= m(h_{2s} - h_1) = 0.05(4149.2 - 2591.3) = 72.895 \text{ kW} \\ \boxed{\dot{W}_{ideal} = 72.895 \text{ kW}} \end{aligned}$$

$$6) \eta_c = \frac{h_{2s} - h_1}{h_{2A} - h_1} = \frac{\dot{W}_{ideal}}{\dot{W}_{actual}} = \frac{4149.2 \frac{\text{kJ}}{\text{kg}} - 2591.30 \frac{\text{kJ}}{\text{kg}}}{4389.30 \frac{\text{kJ}}{\text{kg}} - 2591.30 \frac{\text{kJ}}{\text{kg}}} = 0.866$$

Assume
K_{2s}⁰
ideal

Exam 1 Notes



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? \uparrow - \downarrow

Inside cools

b) Room Temperature? \uparrow - \downarrow Room warms
Room heats due to cooling process

2) Open Fridge

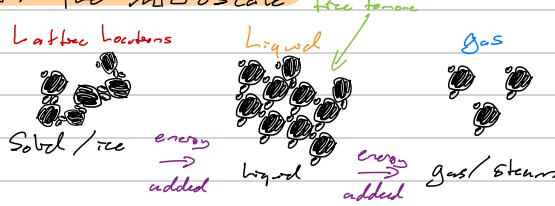
a) Average Room Temp? \uparrow - \downarrow

energy needed to run Fridge, warm room

Two perspectives on energy

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

At the microscale



Takeaway

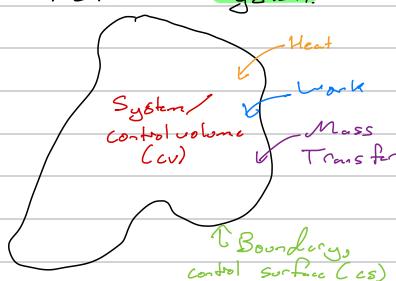
Structure @ Macroscale
dictates Macro state
of energy

→ 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 actual motion. Related closely to temperature
- 5-7: Latent modes. Tied to structural changes
- Sum up \Rightarrow Changes to internal energy
- U or u
- | | |
|--------------|---------------|
| Capital U | Lowercase u |
| Total Energy | mass basis |
| EJ, KJ | $J/Kg...^3$ |

→ Modeling Energy @ the macroscale

Define a System

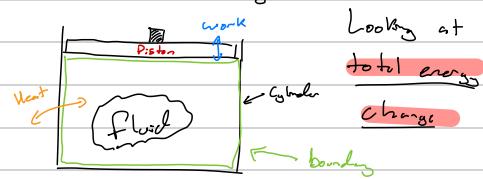


Energy can cross boundary in 3 ways:

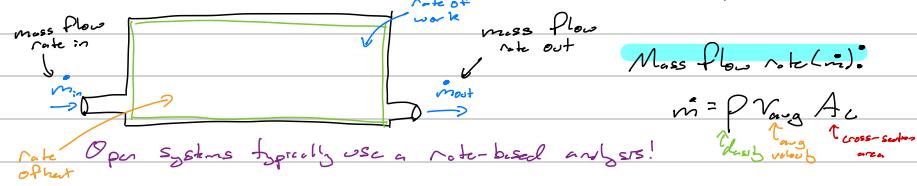
- 1) Heat
- 2) Work
- 3) Mass Transfer

Open vs. Closed Systems

Closed System: No mass transfer across boundary.



Open System: All forms of energy transfer are possible



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:

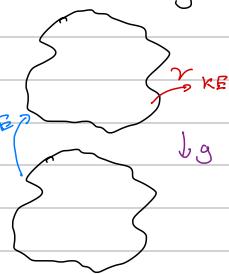
$$\frac{\sum}{m} = e = u + \frac{1}{2} m_A v^2 + g z$$

↑ IE ↑ KE ↑ PE

① Stored Energy

$$E = PE + KE + U$$

↓ KE ↓ PE ↓ U
Kinetic Energy of whole system Internal Energy (IE) Potential Energy



② Energy crossing Boundary

a) Heat Transfer (Q) - energy transfer due to

↑ Q a temperature difference

b) Work (w) - rate of heat transfer over some time

$$Q := \text{rate of heat transfer} \leftarrow \sum K_w, w = \frac{Q}{t}$$

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: $w = \text{Fod}$; force acting over a distance

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

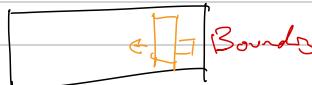
w : Total work over some time $\sum J$

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

→ Different Types of Work

1) Mechanical Work:

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



2) Electrical Work:

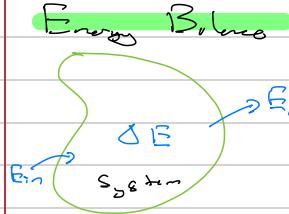


Mass Flow Energy

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

E_{mass} : rate Basis \dot{w}

First Law of Thermodynamics



Combining Equations for unitary law

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

Starting point for Law on total basis

→ On a Rate Basis

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE}{dt}$$

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 variable

Three primary types of substances

- 1) Ideal Gases (or close to/really)
 - Elastic 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

→ or software

Examples of Ideal Gases

- air
- N_2

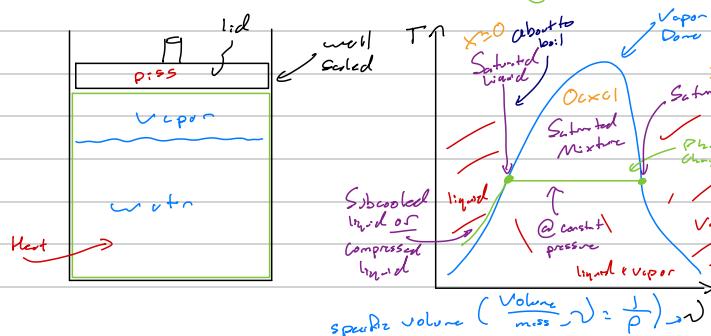
Examples of True Liquids

- water
- oil

Examples of Phase Change Liquids

- water/steam
- refrigerants

Phase Change Process Boiling @ constant pressure



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

Regions

1) Compressed Liquid Region

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

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

2) Saturated Liquid

$$\text{Ques} \rightarrow x = 0, T = T_{sat} \quad P = P_{sat}$$

3) Subcooled mixture

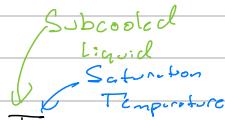
$$0 < x < 1, T = T_{sat} \quad P > P_{sat}$$

4) Saturated Vapor

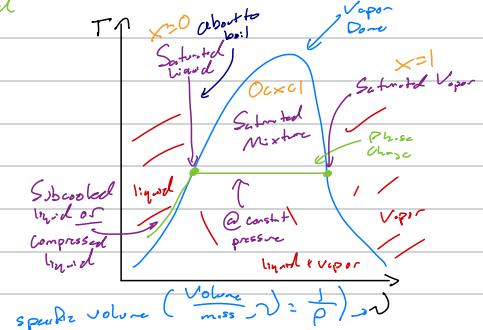
$$x = 1, T = T_{sat} \quad P = P_{sat}$$

5) Superheated vapor

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



Recall:



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

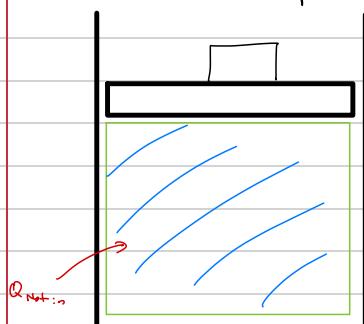
- 1) Start with Saturated mixture table
- 2) Identify the phase (mixture, vapor, or liquid)
- 3) Go to appropriate table

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

$$E_{meas} = E_{mean} = \bar{v} \left(\frac{P}{\rho} + \frac{V^2}{2} + gz \right)$$

Closed Systems

- Consider a piston-cylinder system



1st Law

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

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

$\sum \text{KJ} \rightarrow \frac{\sum \text{KJ}}{\text{kg}}$

$Q_{net,in}$

$-W_{net,out}$

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

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

$$dW = F_{cls} ds$$

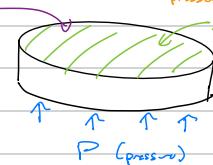
$$= P A_{cls} dv$$

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

Positive when volume increases

Integrate between ① to ②

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



• 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:

most common place to start

• Find Heat Added From ① → ②

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

Heat added only

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

↑ Specific volume

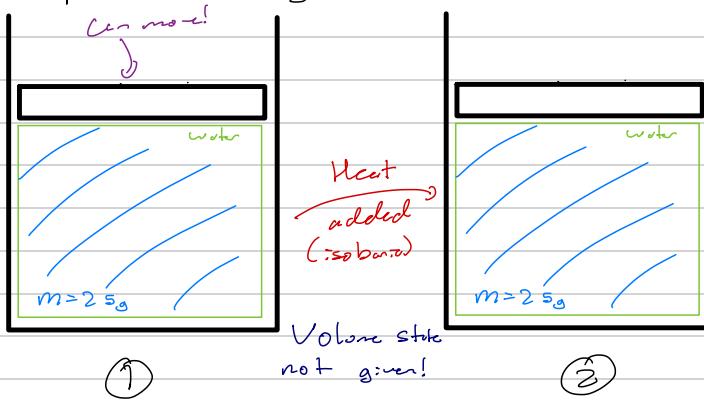
① Go to Sat vapor table @ 300 kPa

Sat $V_{apor}(V_1) = 0.60582 \frac{m^3}{kg}$

Sat $U_{apor}(U_1) = 2543.2 \frac{kJ}{kg}$

Sat Temp = 133°C; 200 > 133 ∴ Superheated

Example: Closed System



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

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

Saturated vapor \Leftrightarrow Treat as phase change fluid

② Go to superheated table @ 0.3 mPa

Position is
 \downarrow
 W_{out}

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

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

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

$$Q_{in} = m(u_2 - u_1) + W_{out} = \boxed{3.5 \text{ kJ}}$$

Polytropic Processes

Boundary Work for a polytropic process

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

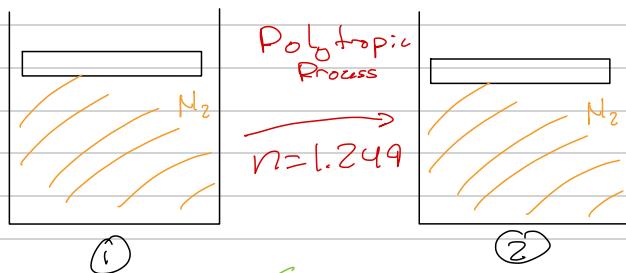
$$P_1 V_1^n = P_2 V_2^n$$

Some Examples

n	constant
0	pressure \rightarrow isobaric
1	temperature \rightarrow isothermal
$\gamma = \frac{C_p}{C_v}$	Entropy \rightarrow isentropic
Gamma = ratio of specific heats	Volume \rightarrow isochoric
$\rightarrow \infty$	only as ideal gas

Example: Piston-Cylinder with

Nitrogen treated as ideal gas



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

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

$$\begin{aligned} V_1 &= 0.07 \text{ m}^3 & V_2 &=? \\ P_1 &= 130 \text{ kPa} & P_2 &= 100 \text{ kPa} \\ T_1 &= 20^\circ \text{C} & T_2 &= 100^\circ \text{C} \end{aligned}$$

Find Work done by Process

Ideal Gas Law / Eq of State

$$PV = nRT$$

$$\text{For ECE225: } PV = mRT$$

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

$$PV = mRT$$

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

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

$$R \text{ vs } \bar{R} : R = \frac{\bar{R}}{M_w}$$

All 3 applicable based on s, l, v and gns!

$$V_2 = \frac{T_2 P_1 V_1}{P_2 T_1} = 0.08636 \text{ m}^3$$

Positive Numbers so this is work out

Finding Δu

3.) Phase change Fluids

a) For a saturated mixture

$$u = X u_g + (1-X) u_f$$

or

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

$$v = X v_g + (1-X) v_f$$

or

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

$h = \dots$ Same for all

$s = \dots$ other tables values

b) For compressed liquids

u, v much stronger functions of temperature than pressure

Shortcut/Estimate: Evaluate compressed liquid properties at the saturation

$$u_{ci}$$

$$v_{ci}$$

$$T$$

$$T_{\text{sat}}$$

$$Q$$

$$T$$

1) Ideal Gases

- Internal energy is only a function of temperature
- Use specific heat value - energy required to increase temperature by 1K (per unit mass) $\sum \frac{u_2 - u_1}{m \cdot K}$
- ↳ Two types:

C_V : Specific heat at constant volume

↳ directly relates to changes in internal energy what we need for closed systems

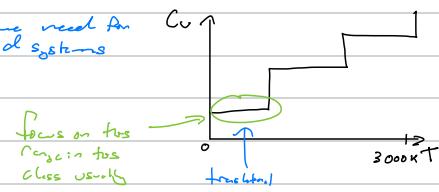
$$C_V = \frac{du}{dT} \rightarrow du = C_V(T)dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 C_V(T)dT$$

C_V is typically constant: $u_2 - u_1 = C_{V,Avg}(T_2 - T_1)$

C_P : Specific heat at constant pressure

↳ directly relates to enthalpy open systems will discuss later



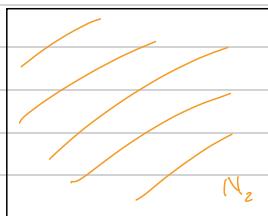
2) True Liquids/Solids

$$\rightarrow C_V = C_P = C$$

$$\left(\Delta u = u_2 - u_1 = \int_1^2 C(T)dT = C_{Avg}(T_2 - T_1) \right) \text{ denotes}$$

$$\left\{ \begin{array}{l} \Delta u = C \Delta T \quad \text{mass specific} \\ \Delta u = m c \Delta T \quad \text{total basis} \end{array} \right.$$

Example: Rigid Tank filled with N₂



Process?



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

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

Rigid Tank = Constant volume

Treat N₂ as an ideal gas

Process is unknown

Steps

1) Write 1st law and simplify

2) Set eqn. to ideal gas

3) Divide T_2 with $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

4) Collect constants and solve

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

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

$$V_1 = V_2 \quad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \rightarrow T_2 = \frac{T_1 P_2}{P_1} = 3T_1 = 3 \times 298 = 894 \text{ K}$$

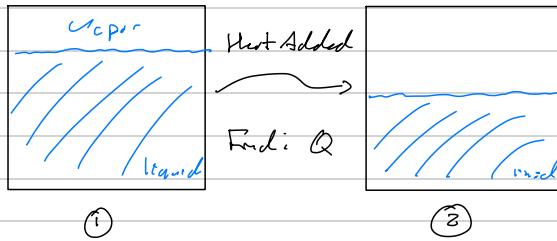
Table lookup

$T \text{ (K)}$	$C_V \left(\frac{u_2 - u_1}{m \cdot K} \right)$
$298 \approx 300$	0.743
$894 \approx 900$	0.849

$$\left. \begin{array}{l} \\ \end{array} \right\} C_{V,Avg} = \frac{0.743 + 0.849}{2} =$$

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

Example 5-30. 10L water in a rigid tank



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

$$x_1 = 0.123$$

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

$$\sqrt{2} = \gamma = 0.207 \frac{\text{m}^3}{\text{kg}}$$

Volume remains the same } $\sqrt{2}x_1 = \gamma$
Mass remains the same

From Sat Water Table @ 100°C

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

From Sat Water Table @ 150°C

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

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

$$\gamma_1 = x_1 \gamma_{g,1} + (1-x_1) \gamma_{f,1} = 0.207 \frac{\text{m}^3}{\text{kg}}$$

$$u_1 = x_1 u_{g,1} + (1-x_1) u_{f,1} = 675.8 \frac{\text{kJ}}{\text{kg}}$$

plus mass

$$\therefore T_2 = 150^\circ\text{C} \quad \left. \begin{array}{l} \text{Go to temperature table @ 150°C} \\ \gamma_2 = 0.207 \frac{\text{m}^3}{\text{kg}} \end{array} \right\}$$

$\gamma < V_f \rightarrow$ compressed liquid

$\gamma > V_g \rightarrow$ superheat vapor

$V_f < \gamma < V_g \rightarrow$ saturated mixture

$$\gamma_2 = \gamma_{f,2} + x_2 (\gamma_{g,2} - \gamma_{f,2}) = 0.207 \frac{\text{m}^3}{\text{kg}}$$

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

Find mixture internal energy value

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

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

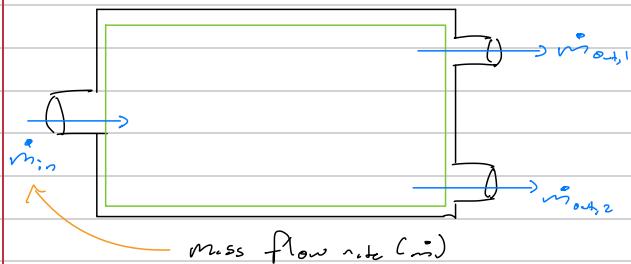
- Find mass? $m = \rho V = \frac{V}{\gamma} = \frac{0.01}{0.207} = 0.048 \text{ kg}$

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

$$\gamma = \frac{V}{m} \quad \rho = \frac{m}{V}$$

$$V = m \gamma$$

Open Systems



- mass crossing in area A

unit time

density ρ $\frac{\text{mass}}{\text{volume}}$
Avg velocity V_{Avg}
Cross sectional area A

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



- No velocity @ the wall

- Linear velocity at center of pipe

velocity profile

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

- Equate \dot{m} expressions
Flow is incompressible

$$\rho V_{\text{Avg}} A_c = \int_{A_c} \rho v_n dA_c$$

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

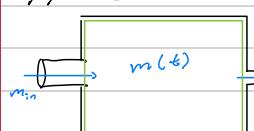
$$\Rightarrow V_{\text{Avg}} = \frac{1}{A_c} \int v_n dA_c$$

Volumetric Flow Rate

$$\dot{V} = \frac{\dot{m}}{\rho} = V_{\text{Avg}} A_c \quad \left(\frac{\text{m}^3}{\text{s}} \right)$$

Conservation Laws

1) Mass



$$m_{\text{in}} - m_{\text{out}} = \Delta m \quad \left(\frac{\text{kg}}{\text{s}} \right)$$

$$m_{\text{in}} - m_{\text{out}} = \frac{dm}{dt} \quad \begin{array}{l} \text{Rate of mass} \\ \text{accumulation} \end{array} \quad \left(\frac{\text{kg}}{\text{s}} \right)$$

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

2) Energy (1st Law Thermodynamics)

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{sys}} \quad \begin{array}{l} \text{(Total basis)} \end{array}$$

$$E_{\text{in}} - E_{\text{out}} = \frac{dE_{\text{sys}}}{dt} \quad \begin{array}{l} \text{Focus for open systems} \\ \text{(Control basis)} \end{array}$$

mass transfer heat work rates of

With focus on steady flow analysis $\Rightarrow \frac{d}{dt} = 0$, in and out balance \Rightarrow 1st law

↳ steady flow devices

\Rightarrow No accumulation of mass or energy inside our system

For Steady Equations

- Mass: $\dot{m}_{\text{in}} = \dot{m}_{\text{out}}$ (or $\dot{m} = 0$)

- Energy: $E_{\text{in}} = E_{\text{out}}$

Corresponds to steady, normal operations

1st Law Steady Open System

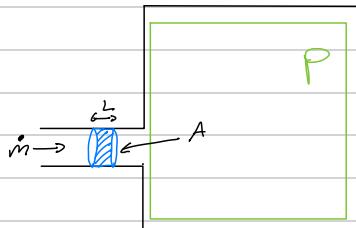
$$(\dot{Q}_{in} - \dot{Q}_{out}) + (\dot{W}_{in} - \dot{W}_{out}) + (\dot{E}_{mass,in} - \dot{E}_{mass,out}) = 0$$

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

\dot{E} mass elements

- (i) Kinetic Energy $(\frac{1}{2} \dot{V}^2_{avg})$
- (ii) Internal Energy (U)
- (iii) Potential Energy ($g z$)
- (iv) Flow Work Energy (P_V)

Flow Work Energy



$$\begin{aligned} W_{flow} &= PL \\ &= PAL \quad \leftarrow \text{from Fluid in with some force} \\ &= PV \end{aligned}$$

$$\frac{W_{flow}}{m} = w_{flow} = \frac{PV}{m} = P_V$$

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

Energy Terms Brought together

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

enthalpy (h)

- Introduce the enthalpy:

$$h = U + PV \quad (\text{also total } H = U + PV)$$

$$\Rightarrow \dot{E}_{mass} = m (h + \frac{1}{2} V_{avg}^2 + gz)$$

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 $z_{out} = z_{in} = 1$

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

Enthalpy Calculating Δh

1) Ideal Gas: $c_p = \frac{dh}{dT} \Big|_P$ @ constant pressure

$$\Rightarrow \Delta h = \int_{T_1}^{T_2} c_p dT$$

2) True Liquids: $c_p = c_v = C$

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

3) Phase Change Fluids

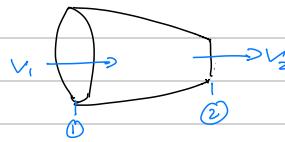
- Tables with mixing rules

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

Steady Flow Devices

1) Nozzles / Diffusers

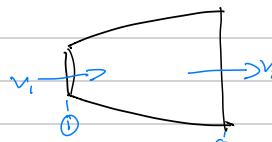
Nozzle



Incompressible ($P_1 = P_2$)

$$\text{mass: } \dot{m}_1 = \rho_1 v_1 A_1 \\ = P_2 v_2 A_2 = \dot{m}_2 \\ \Rightarrow v_2 \uparrow \text{ as } A \downarrow, P_2 < P_1$$

$D_f, f, R_{\text{nozzle}}$



$$v \downarrow \text{ as } A \uparrow, P_2 > P_1$$

$$\text{Energy Analysis: } \dot{Q}_{\text{nozzle}} + \dot{W}_{\text{nozzle}} = \dot{m} [h_2 - h_1 + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)]$$

Nozzle and diffuser Assumptions: $\Delta PE \approx 0$ ($z_2 \approx z_1$)

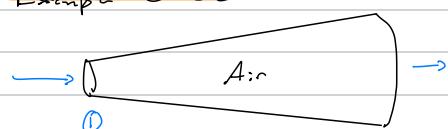
$$\dot{Q}_{\text{nozzle}} = 0 \text{ (adiabatic)}$$

$$\dot{W}_{\text{nozzle}} = 0 \text{ (positive sign)}$$

Exchanges enthalpy for kinetic Energy

Example 6-26

Take air as ideal



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

$$T_1 = 30^\circ\text{C}$$

$$v_1 = 350 \frac{\text{m}}{\text{s}}$$

$$P_2 = 200 \text{ kPa}$$

$$T_2 = 40^\circ\text{C}$$

$$v_2 =$$

Find v_2 , something about the areas?

$$\text{Energy: } 0 = \dot{m} [(h_2 - h_1) + \frac{1}{2}(v_2^2 - v_1^2)]$$

$$\cancel{\dot{m}}(h_2 - h_1) = \cancel{\dot{m}}(\frac{1}{2})(v_2^2 - v_1^2)$$

$$2(h_2 - h_1) = v_2^2 - v_1^2$$

$$v_2 = \sqrt{v_1^2 - 2(h_2 - h_1)}$$

Need to calculate Δh

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

$$\Rightarrow v_2 = \sqrt{v_1^2 - 2c_p A_{\text{avg}}(T_2 - T_1)} = 40.7 \frac{\text{m}}{\text{s}}$$

$$\boxed{\frac{m^2}{s^2} = \frac{J}{kg}}$$

$$\text{mass: } \dot{m}_1 = \dot{m}_2 \\ P_1 v_1 A_1 = P_2 v_2 A_2 \rightarrow \frac{A_2}{A_1} = \frac{P_1 v_1}{P_2 v_2} \quad \text{If } P \text{ is constant} \rightarrow \frac{A_2}{A_1} = \frac{V_1}{V_2} = 0.6$$

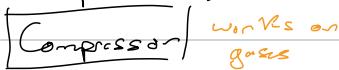
$$\rightarrow \text{use ideal gas Eq: } P = \frac{P}{RT}, P_1 = \frac{P_1}{RT_1} \text{ and } P_2 = \frac{P_2}{RT_2}$$

Don't make bad assumptions

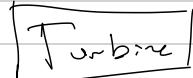
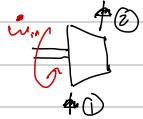
$$\frac{P_1 v_1}{P_2 v_2} = \frac{V_1}{V_2} \left(\frac{P_1}{RT_1} \frac{RT_2}{P_2} \right) = 8.6 \quad \text{Area ratio should be 5.1}$$

5

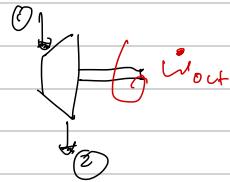
2) Compressors / Turbines



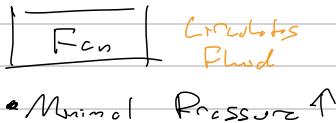
- As $P \uparrow$, so does T_{mp}



- Extracts fluid power to produce shaft work



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



- Minimal Pressure \uparrow

Types of
Compressors

Energy Analysis

$$Q_{net,in} + W_{net,in} = \dot{m} [h_2 - h_1] + \frac{1}{2} (V_2^2 - V_1^2) + g (z_2 - z_1)$$

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

Reduces Q & typically small

$$\Delta KE \approx 0 \text{ desired flow}$$

KE converted to Btu/lb_p w/ it loses devices
Focuses on Δh vs. $W_{net,in}$.

$$W_{net,in} = \dot{m} (h_2 - h_1)$$

$$(W_{in} - W_{out}) = \dot{m} (h_2 - h_1)$$

Example 6-42 Conditions provided for adiabatic steam turbine

$$(1) P_1 = 10 \text{ MPa}$$

$$T_1 = 500^\circ\text{C}$$

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



$$\left. \begin{array}{l} P_1 \\ T_1 \end{array} \right\} \text{Steam Tables} \xrightarrow{\text{SH}} h_1 = 3828 \frac{\text{kJ}}{\text{kg}}$$

$$\left. \begin{array}{l} P_2 \\ \text{Subcritic} \end{array} \right\} \xrightarrow{10 \text{ kPa}} h_g = 191.82 \frac{\text{kJ}}{\text{kg}}$$

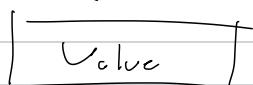
$$h_P = 2583.9 \frac{\text{kJ}}{\text{kg}}$$

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

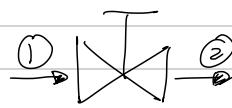
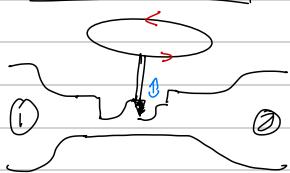
- Find W_{out} for $\dot{m} = 2 \frac{\text{kg}}{\text{s}}$

$$W_{out} = 2 \frac{\text{kg}}{\text{s}} (3828 - 2344.2) \frac{\text{kJ}}{\text{kg}} = 2061 \text{ kW} = 2.06 \text{ MW}$$

3) Throttles \rightarrow Valve



Controls Flow,
Control Pressure



$$\dot{Q}_{\text{heat}} + \dot{W}_{\text{work}} = m [h_2 - h_1 + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)]$$

Assumptions: $\Delta P_E \approx 0$

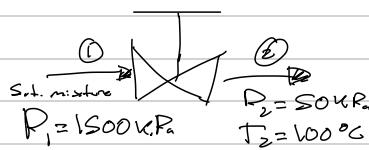
$\Delta K_E \approx 0$

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

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

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

Example: Steam flows through a valve



$$1^{\text{st}} \text{ Law: } h_1 = h_2$$

$$\left. \begin{array}{l} P_2 \\ T_2 \end{array} \right\} \text{Steam} \xrightarrow{\text{STAB}} h_2 = 2682.4 \frac{\text{kJ}}{\text{kg}} = h_1$$

• Final Q_{heat} @ inlet

$$\left. \begin{array}{l} h_1 = 2684.2 \\ P_1 = 1500 \text{ kPa} \end{array} \right\} \text{Steam mix} \Rightarrow h_1 = h_g + x(h_p - h_g) \Rightarrow x = \frac{h_1 - h_g}{h_p - h_g}$$

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

$$h_g = 2741.0 \frac{\text{kJ}}{\text{kg}}$$

$$\Rightarrow x = 0.44$$

Recap

$$(i) \text{ Nozzles / Drafts} \quad (h_2 - h_1) + \frac{1}{2}(v_2^2 - v_1^2) = 0$$

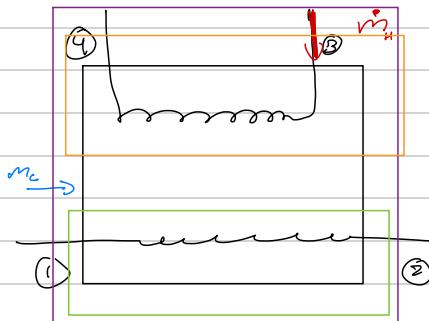
$$(ii) \text{ Compressors / Turbines} \quad \dot{W}_{\text{net}} = m(h_2 - h_1)$$

(iii) Turbines

$$h_1 = h_2$$

Heat Exchangers

Transfers heat from hotter fluid to colder fluid



Energy Analysis

$$(Q_{\text{in}} - Q_{\text{out}}) + (h_1 - h_2) = m [h_2 - h_1 + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)]$$

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

$\Delta K_E \approx 0$

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

If Boundary is Purple

$$\dot{Q}_{\text{heat}} = m_H(h_2 - h_1) + m_C(h_2 - h_1)$$

If Boundary is Green

$$\dot{Q}_{\text{in}} = m_C(h_2 - h_1)$$

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{out}}$$

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

If Boundary is Orange

$$\dot{Q}_{\text{out}} = m_H(h_2 - h_1)$$

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 → 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

into work.

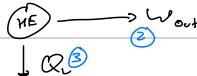
(iii) Rejects heat to a low-temp reservoir at T_L

(iv) Operates as a cycle

↓ lessable ↑ unusable

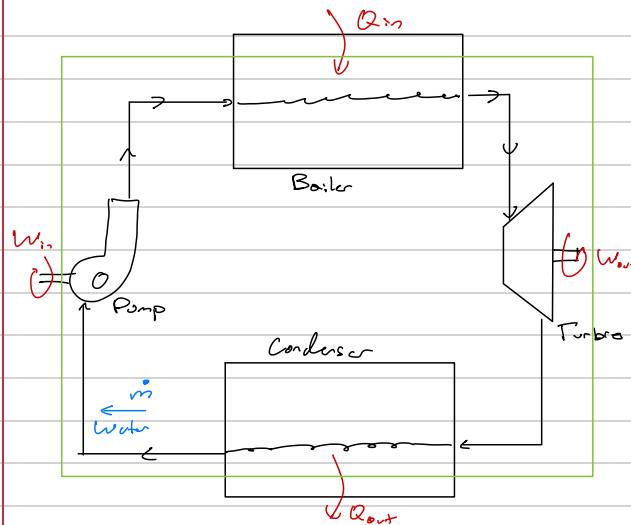
T_H

$Q_H \text{ (1)}$



T_L

Power Plant as a heat engine (Rankine Cycle)



1st Law Analysis

$$(Q_{in} - Q_{out}) + (W_{in} - W_{out}) = m(u_2 - u_1)$$

Boiler Condenser pump turbine Operates as a cycle

$T_H \sim$ Combustion Temperature

$$Q_H = Q_{in}$$

$$HE \rightarrow W_{out} = W_{out} - W_{in}$$

$$Q_L = Q_{out}$$

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

- Define Thermal Efficiency

$$\eta_{th} = \frac{W_{out} - W_{in}}{W_{out} - W_{in} - Q_{out}} = \frac{W_{out} - W_{in}}{Q_{in}} \rightarrow \eta_{th} = \frac{W_{out} - W_{in}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_L}{Q_{in}}$$

[1st Law]

Typical Thermal Efficiencies

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

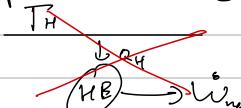
- Diesel Engine: $\eta_{th} \approx 40\%$

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

\rightarrow Define the ideal heat engine

\hookrightarrow Carnot Cycle

- From ideal heat engine from ideal processes

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

\rightarrow Idealizations on an actual process

- Pump - reversible compression: Requires minimum work

- Turbine - reversible expansion: Produce maximum work

\rightarrow 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

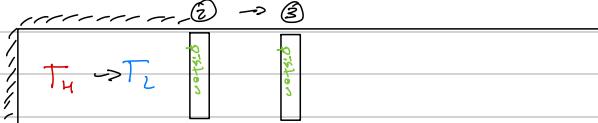
(vi) Electrical Resistance

\rightarrow Carnot Heat Engine (Ideal Heat Engine)

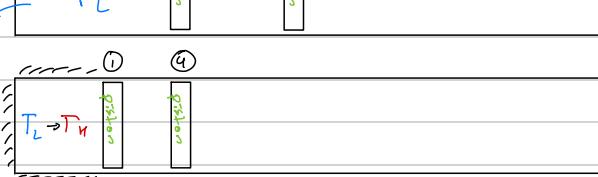
① \rightarrow ②



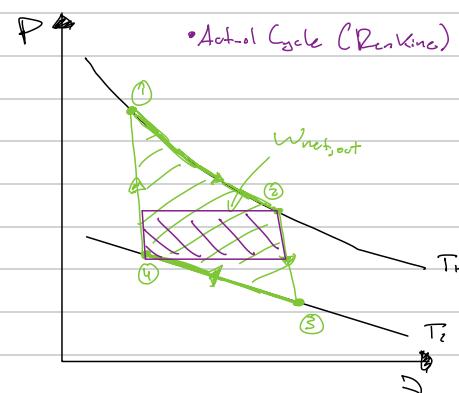
② \rightarrow ③



③ \rightarrow ④



④ \rightarrow ①



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

Actual Steps in Cycle

Actual steps in cycle

a) Isothermal expansion @ T_H

b) Adiabatic expansion: $T_H \rightarrow T_L$

cooling

c) Isothermal compression @ T_L

d) Adiabatic compression

Area under the curve

or above curve

Carnot Principles

- 1) Efficiency of an irreversible (Actual) 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

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

→ For a heat engine (general):

$$\eta_{\text{gen}} = \frac{W_{\text{net,out}}}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

→ For a Carnot heat Engine:

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

Refrigeration Cycles & Heat Pumps

Refrigeration Cycle

T_H

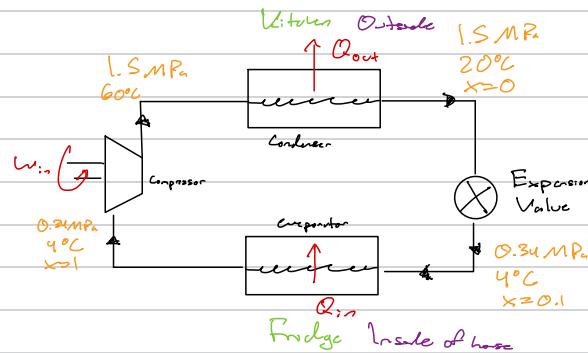
$$w_{in} \rightarrow (R) \uparrow Q_H$$

$$\uparrow Q_L$$

T_L

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)

$$COP_R = \frac{Q_{in}}{w_{in}} = \frac{Q_L}{w_{in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1} \Rightarrow COP_R > 1 \quad \text{abides by 2nd Law so } Q_H \neq Q_L$$

COP also known as R₂ 1st Law Relationship

Typical Values: $COP_R = [2, 6] \leftarrow$ 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 $COP_{R,ideal} > COP_R, \text{ generally}$

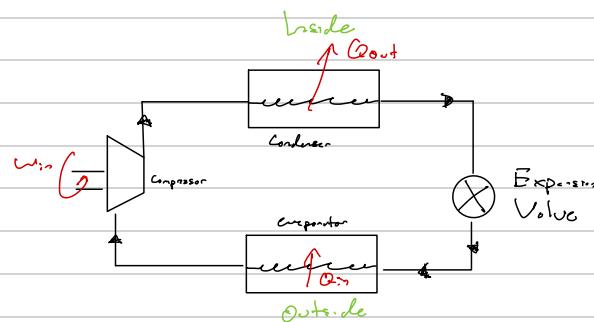
Heat Pump

T_H

$$w_{in} \rightarrow (HP) \uparrow Q_H$$

$$\uparrow Q_L$$

T_L



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

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

Carnot

Two Types of Heat Pumps

1) Air Source

$\hookrightarrow T_L$ is the air

2) Ground Source

$\hookrightarrow T_L$ is the ground

Example 7 - S3

- Heat Pump Given
- 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

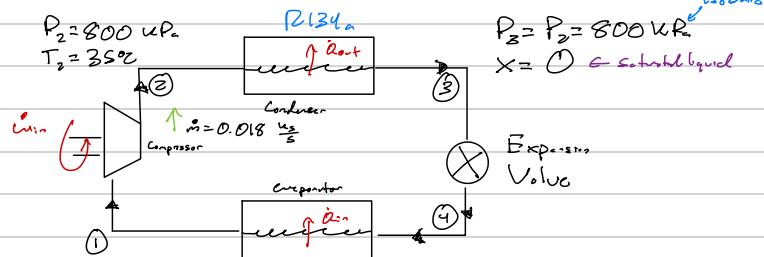
$$\text{CoP}_{\text{HP}} = \frac{\dot{Q}_{\text{out}}}{\dot{W}_{\text{in}}} = \frac{?}{1.2 \text{ kW}}$$

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

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

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

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



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

1st Law, open system

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

Tables: (3)

$$\begin{aligned} T_2 = 35^\circ\text{C} \\ P_2 = 800 \text{ kPa} \end{aligned} \quad \begin{cases} \text{SH} \\ \text{Liquified to liquid}_2 \end{cases} \Rightarrow h_{310} = \dots \quad h_{400} = \dots \quad h_2 = 271.2 \frac{\text{kJ}}{\text{kg}}$$

DBUL tables (3)

in propert

$$\begin{aligned} A-1/\text{K} \quad x=0 \\ P_3 = 800 \text{ kPa} \end{aligned} \quad \begin{cases} \text{Saturated} \\ \text{Liquid} \end{cases} \Rightarrow h_f = h_b = 24.48 \frac{\text{kJ}}{\text{kg}}$$

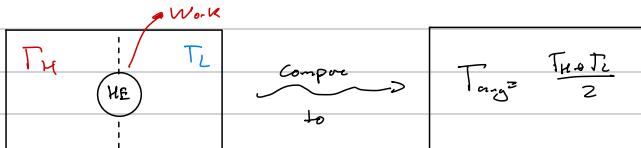
$$\rightarrow \dot{Q}_H = \dot{m}(h_2 - h_3) = 3.16 \text{ kW} = \dot{Q}_{\text{out}}$$

Entropy

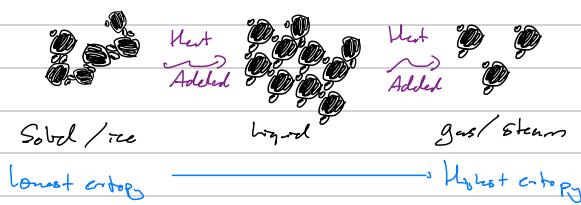
- For cycles / processes
 - Ideal cycles/processes \rightarrow reversible
 - Real cycles/processes \rightarrow irreversible
- Irreversibility \Rightarrow entropy generation

Want to think about entropy

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



(ii) Entropy as a measure of molecular system disorder



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

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

↑ Total change $\sum \frac{dQ}{T}$
in entropy $\sum \frac{dS}{T}$

Make sure you're using absolute temperature!

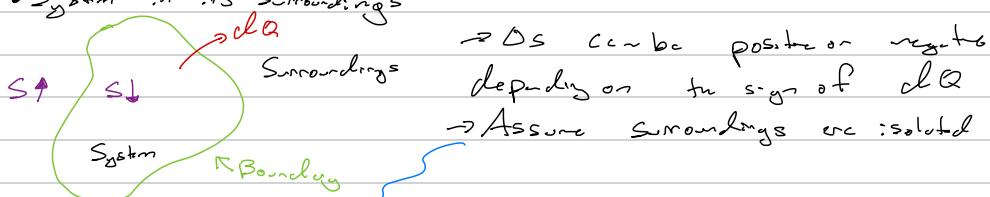
\hookrightarrow Mass specific basis: $d_s = \frac{dS}{m} \leq \frac{dS}{kg}$

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



No heat or work out of the surroundings

- Total Entropy change is always positive

$$\Delta S_{\text{tot}} = \Delta S_{\text{sys}} + \Delta S_{\text{surroundings}}$$

Three Possibilities

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

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

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

- For a real system:

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

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

Calculating Entropy Change

1) Isothermal Process (valid for surroundings)

Assume fixed temperature T_0

$$\Delta S_{\text{sur}} = \int_{T_1}^{T_2} \frac{dQ}{T} = \int_{T_0}^{T_2} \frac{dQ}{T_0} = \frac{-Q_2}{T_0}$$

Heat Transfer from T_1 to T_2

2) More Generally

$$dQ - dU = dH$$

$dS = \frac{dQ}{T}$ $dU = \underbrace{dH}_{(Q_{\text{int}} - PdV)} - \underbrace{dP}_{\text{bond work}}$ $\underbrace{dH}_{\text{Enthalpy}}$

$$TdS - PdV = dH$$

Divide by mass:

$$TdS = dU + PdV$$

Gibbs Equations

Gibbs Equation - enthalpy form

$$TdS = dU + PdV$$

$$\bullet \text{Recall: } h = u + Pv$$

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

$$\Rightarrow du = dh - PdV - VdP$$

$$TdS = dh - PdV - VdP$$

$$TdS = dh - VdP$$

Evaluating ΔS°

1) Phase change fluids

→ Use tables for s_2, s_1

2) Ideal Gases

$$TdS = du + PdV$$

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

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

This is Prankur's way

$$\rightarrow \text{Ideal Gas Internal Energy: } du = C_V dT$$

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

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

→ 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 P → 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 given quantities

3) True (Incompressible) liquids/solids

$$TdS = du + PdV$$

$$TdS = dh - VdP$$

$$\rightarrow TdS = C_V dT$$

$$\rightarrow TdS = C_p dT$$

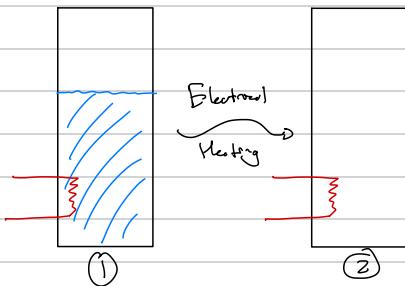
$$\text{Generally: } TdS = C dT$$

→ Integrate:

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

Exams will be more application based instead of derivation based

Example 8-30) Multi-insulated tank w/ 3 kg water



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

$\frac{3}{4}$ of mass is liquid
↓

All vapor (\approx superheat)
 $T_2 = T_1$

Find: Δs_{sys} $\left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}} \right)$
Start at table:

$$Q_{\text{add}} \quad Q_1: x_1 = \frac{1 - g_{\text{sat}}}{1 + g_{\text{sat}}} = 0.25$$

$$P_1 \quad \begin{cases} \text{Sat.} \\ \text{max} \end{cases} \quad S_f = 1.8302 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$x_1 \quad S_g = 7.127 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$\begin{cases} \text{Sat.} \\ \text{max} \end{cases} \quad \begin{cases} \text{Vap.} \\ \text{max} \end{cases} \quad \begin{aligned} \bar{v}_f &= 0.001061 \frac{\text{m}^3}{\text{kg}} \\ \bar{v}_g &= 0.88578 \frac{\text{m}^3}{\text{kg}} \end{aligned} \quad \begin{aligned} \bar{v}_1 &= x_1 \bar{v}_g + (1-x_1) \bar{v}_f = 0.222 \frac{\text{m}^3}{\text{kg}} \end{aligned}$$

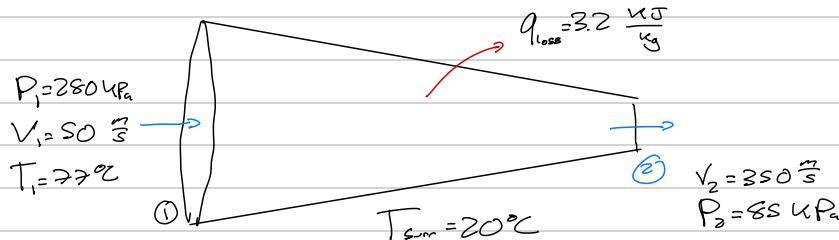
Quality 2: $x_2 = 1$, all vapor \rightarrow int. point

$$\begin{cases} \text{Vap.} \\ \text{max} \end{cases} \quad \begin{cases} \text{Sat.} \\ \text{Vap.} \end{cases} \quad S_2 = S_g = 6.63 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

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

Look for $0.222 \frac{\text{m}^3}{\text{kg}}$ on
Tables or Temp tables

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



Find: a) T_2
b) Δs_{total} $\left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}} \right)$

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

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

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

$$P_{\text{exit}} \rightarrow T_2 = 24.11^\circ\text{C}$$

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

System given pressure, use enthalpy form

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

$$c_{p,\text{air}} = 1.005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

Surroundings treat surroundings as isothermal with respect to surroundings

$$\Delta s_{\text{sur}} = \frac{Q}{T_0} \quad \Delta s_{\text{sur}} = \frac{q_{\text{loss}}}{T_0} = \frac{+3.2}{20 + 273.15} \frac{\text{kJ}}{\text{kg}\cdot\text{K}} = 0.01 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

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

- $\Delta s_{\text{isent}} = 0$

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

- By substance type

(i) Phase Change Fluids \rightsquigarrow tables

$$\Rightarrow s_2 = s_1$$

(ii) Ideal Gases

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

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

- Ratio of specific heats: $K = \frac{C_p}{C_v} \quad \Rightarrow \frac{R}{c_v} = K-1$

- For ideal gases: $R = C_p - C_v \quad \Rightarrow \frac{R}{c_v} = K-1$ (K is also the ratio)

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

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

Then T_{2s} as output of process

- Starts with enthalpy P_1 for m...

$$\Delta s_{\text{isent}} = c_{p,\text{avg}} \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right) = 0 \quad \xrightarrow{\text{isentropic process}}$$

Similar analysis

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

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

- 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: caution out for assumptions when problem-solving

(iii) True Liquids/Solids

$$\Delta s_{\text{isent}} = C \ln \left(\frac{T_2}{T_1} \right) = 0 \quad \xrightarrow{\text{isentropic}}$$

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

For solvents/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)

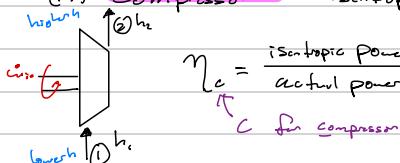


$$\eta_t = \frac{\text{Actual power}}{\text{Isentropic power}} = \frac{m(h_1 - h_2)}{m(h_1 - h_{2s})} = \frac{h_1 - h_{2s}}{h_1 - h_2}$$

+ for turbine

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

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



$$\eta_c = \frac{\text{Isentropic power}}{\text{Actual power}} = \frac{m(h_{2s} - h_1)}{m(h_{2s} - h_2)} = \frac{h_{2s} - h_1}{h_{2s} - h_2}$$

C for compression

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

Example 8-118) Adiabatic CO₂ Compressor

② P₂ = 600 kPa
T₂ = 450 K

① P₁ = 100 kPa
T₁ = 300 K
 $m = 18 \frac{\text{kg}}{\text{s}}$

$\eta_c = \frac{h_{2s} - h_1}{h_{2A} - h_1} = \frac{CP_{CO_2} (T_{2s} - T_1)}{CP_{CO_2} (T_{2A} - T_1)}$

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

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

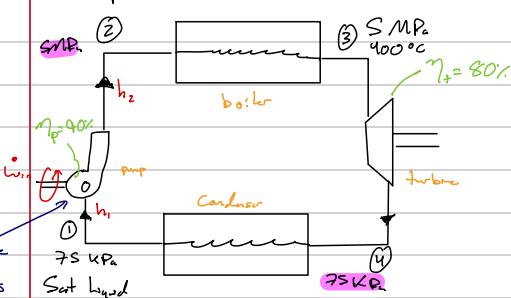
$\therefore \eta_c = \frac{(434.2 \text{ K} - 300 \text{ K})}{(450 \text{ K} - 300 \text{ K})} = 0.845$

$\boxed{\eta_c = 84.5\%}$

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



Cannot assume
the pump is
isothermal

• Find η_{th} compared to η_{carnot}

Boiler & compressor are

both isobaric (constant P) Looks at best-case - State (2s) : $s_2 = s_1 = 1.2182 \frac{kJ}{kg \cdot K}$

Interpolation not on exam 3

State (1)

$$P_1 = 75 \text{ kPa} \xrightarrow{\text{sat}} T_1 = 91.76^\circ\text{C}, s_p = s_1 = 1.2182 \frac{kJ}{kg \cdot K}$$

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

$$\text{Note: } \dot{W}_{\text{pump}} = \dot{V}_p = \dot{m}(h_2 - h_1)$$

(1) Isentropic compression from (1) → (2)

$$\text{Look at best-case - State (2s) : } s_2 = s_1 = 1.2182 \frac{kJ}{kg \cdot K}$$

• For actual pump:

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

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

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

State (2)

$$P_2 = 5 \text{ MPa} \xrightarrow{\text{sat}} s_2 = s_1 = 1.2182 \xrightarrow{\text{mix}} s_2 < s_{2s} < s_{2g} \xrightarrow{\text{comp.}} h_{2s} = 390.107 \frac{kJ}{kg}$$

interpolate

$$s_{200} < s_2 < s_{100}$$

State (3)

$$T_3 = 400^\circ\text{C} \xrightarrow{s_1} h_3 = 3146.2 \frac{kJ}{kg}$$

$$P_3 = 5 \text{ MPa} \xrightarrow{s_1} s_3 = 6.6483 \frac{kJ}{kg \cdot K}$$

Isentropic expansion from (3) → (4s)

$$P_4 = 75 \text{ kPa} \xrightarrow{\text{sat}} x_{4s} = 0.871 \xrightarrow{\text{from}} s_4 = s_3 = 6.6483 \frac{kJ}{kg \cdot K}$$

$$h_{4s} = 2382.8 \frac{kJ}{kg}$$

From x_{4s}, h_f, h_g

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

$$\Rightarrow h_{4a} = 2533.6 \frac{kJ}{kg}$$

$$\dot{W}_{\text{turbine}} = \dot{V}_t = \dot{m}(h_3 - h_{4a}) = \dot{m}(663) \text{ kW}$$

Boiler heat addition

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

Thermal Efficiency (η_{th})

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

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

Carnot Efficiency (η_{carnot})

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

$$= 1 - \frac{400}{91.76} = 45.8\%$$

$$\leftarrow \text{temp into turbine}$$

Pressure (MPa) vs. Enthalpy (kJ/kg) Plot

