

Engineer

- Latin root

Thermodynamics

dynamics - motion

Thermo - flow of energy

because of difference of temp.

First transfer of heat \rightarrow power

The steam engine

Start with heat and get out motion

James Watt

improve efficiency of steam engines

Transfer of Thermo energy to dynamic energy

classical thermodynamics

macroscopic view, no atoms/molecules

statistical thermodynamics

accounts for microscopic components probabilistically

what is a system?

- the part of the universe which we focus our attention

surrounding

everything not the system

boundary

separates system and surrounding

energy \wedge passes through it

and mass

closed system

no mass crossing the boundary

Select a control mass

isolated system

an absolutely closed system with no change in mass or energy

only seen at small time steps

open system

mass crosses the boundary

a control volume

Applying the same logic to the other two components of the vector
we get the following results:
Component 1: $\vec{v}_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$
Component 2: $\vec{v}_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$
Component 3: $\vec{v}_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$
These three vectors are linearly independent and form a basis for the space.
Therefore, we can write:
$$\vec{v} = v_1 \vec{v}_1 + v_2 \vec{v}_2 + v_3 \vec{v}_3$$

$$\vec{v} = v_1 \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + v_2 \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + v_3 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

This shows that any vector in the space can be written as a linear combination of the basis vectors.

$$r^2 = 28.97 \quad \text{and} \quad \theta = 45^\circ$$

$$x = r \cos \theta \quad y = r \sin \theta$$

can not have a system open to mass but not energy

if mass enters, there is kinetic energy

properties of a system

numbers that describe it

- temp • volume • mass • energy • pressure • density

change in properties is a property

extensive properties

sum of the subsystems properties gives the systems properties

- mass • volume • energy

intensive properties

not additive

- you don't add all temps to get the total

- temp • pressure • density

state of a system

- ~ value of all its properties

equation of state

relationship between different properties

change in state

thermodynamic process

equilibrium

final steady state of a system once it is isolated

all properties are balanced

Types

Mechanical, Thermal, Phase, chemical

chapter 1:

all values and quantities can only be measured in comparison to a reference

numbers only have meaning when accompanied by measuring units

if one can identify a test volume V , they can have a continuum hypothesis

$$p = \lim_{V \rightarrow V'} (m/V)$$

when in equilibrium, $m = p \cdot V = \iiint p dV$
specific volume $v = 1/p$ (m^3/kg)

molecular weight: M

molar specific volume $\bar{v} = v \cdot M$

Absolute thermodynamic pressure

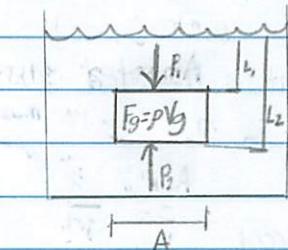
normal pushing force per unit area that an infinitely small subsystem exerts on the surroundings

pressure does not depend on orientation of surface

$$1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg/ms}^2, 1 \text{ bar} = 10^5 \text{ Pa}$$

$$1 \text{ atm} = 1.01325 \text{ bar}$$

Archimedes' Principle and Barometer



$$F_g = pg(L_2 - L_1)A$$

$$P_1 \cdot A + pg(L_2 - L_1)A = P_2 \cdot A$$

$$P_1 + pg(L_2 - L_1) = P_2$$

$$P_2 - P_1 = pg(L_2 - L_1)$$

gauge pressure: pressure relative to the atm

Absolute thermodynamic temperature

Kelvin: 0 as absolute and 273.15 is temp for waters triple point $\leftarrow 491.67^\circ R$

Zeroth principle of thermodynamics: if system A is in thermal equilibrium and B is in equilibrium, A and B are in equilibrium with each other

$$T_{\text{steam}} = \lim_{P_c \rightarrow 0} \left(\frac{P_s}{P_i} \right) = 1.36099$$

Thermal energy and absolute temp.

- thermal energy is associated with movement of the atoms and molecules that make matter
- abs. temp. is just the energy of movement of molecules

Energy and energy transfer - chapter 2

$$\text{Work} = \vec{F} \cdot d\vec{s} = \left(m \frac{d\vec{v}}{dt} \right) \cdot d\vec{s} = m \vec{v} d\vec{v}$$

* $d\vec{s} = \vec{v} dt$

$$\text{Work} = \int m \vec{v} d\vec{v}$$
$$\text{Work} = \Delta \frac{1}{2} m \vec{v}^2$$

$$\text{Power} = \dot{W} = \vec{F} \cdot \vec{v}$$

First law of Thermodynamics: Conservation of energy is all mechanical energies, potential energies and internal energy.

Total change in energy is always zero. per mass per mole

$$\Delta E = \Delta U + \Delta PE + \Delta KE$$

$$U, \bar{U}$$

$$e: \text{specific energy per mass} = E/m$$

$$PE, \bar{PE}$$

$$\bar{E} = E/n * \text{per mole}$$

$$KE, \bar{KE}$$

Storing energy in a system

Batteries, springs

Energy balance for a closed system:

$$\Delta E = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) = \Delta U + \Delta KE + \Delta PE$$

= Work and heat

Thermodynamic work and power

• Gibbs

• work is any form of interaction involving transfer of energy

• (+) work (out)

• done by the system to the surroundings

• (-) work (in)

• surroundings onto system

$$W = \frac{dW}{dt} = \text{power}$$

• work is not a property because the process matters, not just initial and final state

types of work.

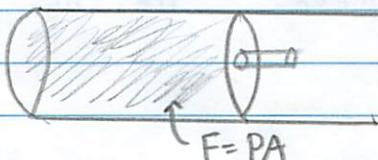
normal stress:

$$\sigma = \frac{F}{A} \quad F = \sigma A \quad W = F \cdot dx = \sigma A \cdot dx = \int \sigma dV$$

surface tension: $\tau = \frac{F}{l}$

$$W = \int F \cdot dx = \int \tau \cdot l \cdot dx = \int \tau \cdot dA$$

Expansion (compression) work at constant pressure



if $dV > 0 \rightarrow W > 0$
 $dV < 0 \rightarrow W < 0$

Nathan Stenseng Thermo HW 1

1.5

Perform the following unit conversions

$$\text{a. } \frac{122 \text{ in}^3}{12 \text{ in}} \left| \begin{array}{c} 1 \text{ ft} \\ 12 \text{ in} \end{array} \right| \frac{1 \text{ ft}}{12 \text{ in}} \left| \begin{array}{c} 1 \text{ ft} \\ 12 \text{ in} \end{array} \right| \frac{1 \text{ L}}{0.0353 \text{ ft}^3} = 2 \text{ L}$$

$$\text{b. } \frac{778.17 \text{ ft} \cdot \text{lbf}}{1 \text{ ft} \cdot \text{lbf}} \left| \begin{array}{c} 1.35582 \text{ J} \\ 1,000 \text{ J} \end{array} \right| \frac{1 \text{ kJ}}{1,000 \text{ J}} = 1.055 \text{ kJ}$$

$$\text{c. } \frac{100 \text{ hp}}{1.341 \text{ hp}} \left| \begin{array}{c} 1 \text{ kW} \\ 1 \text{ hp} \end{array} \right| = 74.57 \text{ kW}$$

$$\text{d. } \frac{1000 \text{ lb}}{1 \text{ h}} \left| \begin{array}{c} 0.4536 \text{ kg} \\ 1 \text{ lb} \end{array} \right| \frac{1 \text{ h}}{60 \text{ s}} = 7.56 \text{ kg/s}$$

$$\text{e. } \frac{29.392 \text{ lbf}}{\text{in}^2} \left| \begin{array}{c} 1 \text{ N} \\ \text{m}^2 \end{array} \right| \frac{10^2 \text{ lbf}}{1.4504 \text{ lbf}} \left| \begin{array}{c} \text{in}^2 \\ 10^5 \text{ N} \end{array} \right| = 2.03 \text{ bar}$$

$$\text{f. } \frac{2500 \text{ ft}^3}{\text{min}} \left| \begin{array}{c} 1 \text{ min} \\ 60 \text{ sec} \end{array} \right| \frac{0.0283 \text{ m}^3}{1 \text{ ft}^3} = 1.179 \text{ m}^3/\text{s}$$

$$\text{g. } \frac{75 \text{ mile}}{\text{h}} \left| \begin{array}{c} \text{h} \\ 1 \text{ mile} \end{array} \right| \frac{60.93 \text{ km}}{\text{h}} = 120.6975 \text{ km/h}$$

$$\text{h. } \frac{2000 \text{ lbf}}{1 \text{ lbf}} \left| \begin{array}{c} 4.4482 \text{ N} \\ 1 \text{ lbf} \end{array} \right| = 8896.4 \text{ N}$$

1.14

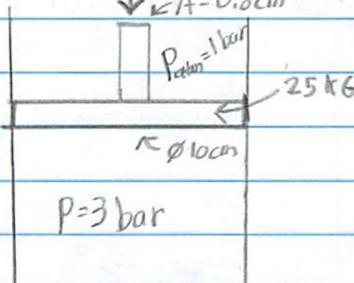
$$4400 = 9.81 \cdot N$$

$$N = 448.52$$

$$\downarrow F \quad A = 0.8 \text{ cm}^2$$

$$448.52 \cdot 0.224 = \boxed{100.47 \text{ N}}$$

1.24

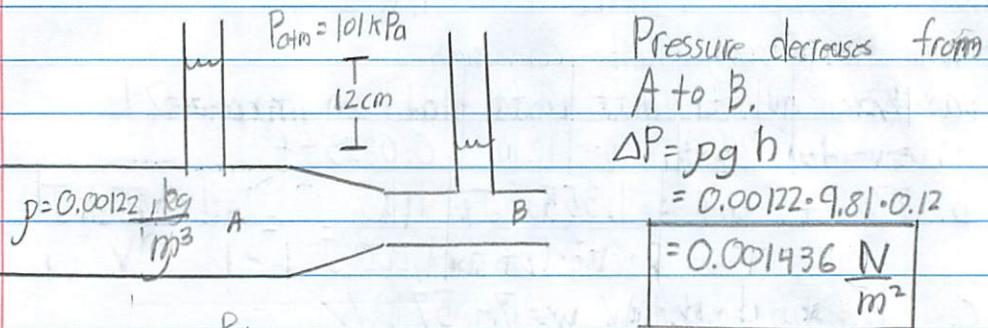


$$3 \cdot \frac{\pi}{4} (10)^2 = 25 \cdot 9.81 + 1 \cdot \frac{\pi}{4} 10^2 + F$$

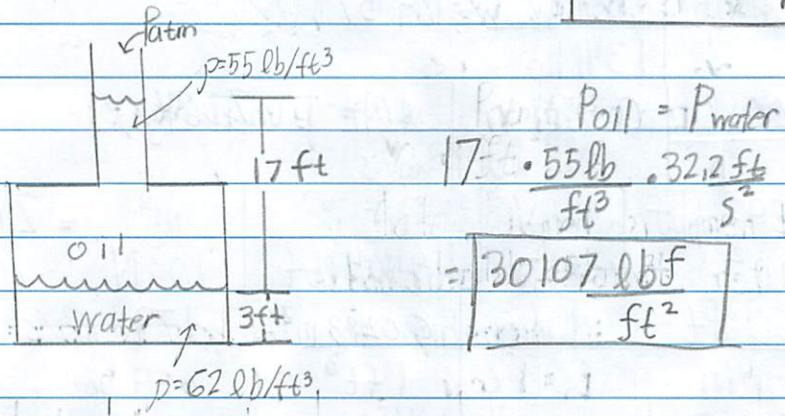
$$F = 0.728 \text{ N}$$

$$P = 3 \text{ bar}$$

1.29



1.40



1.43

$$24^\circ\text{C} = 297.15 \text{ K} = 534.87^\circ\text{R} = 75.2^\circ\text{F}$$

Polytropic Process

prototypic quasi-equilibrium process that can interpolate experimental data

$$p \cdot V^n = \text{constant} = p_1 \cdot V_1^n = p_2 \cdot V_2^n$$

$n=0$; $V=1$, $p \cdot V$, isobaric

$n \rightarrow \infty$, isochoric, $W=0$

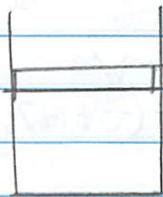
$$p = \frac{p_1 V_1^n}{V^n}$$

$$W = \int_{V_1}^{V_2} p \cdot dV = p_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V} = p_1 V_1 \ln(V_2/V_1)$$

constant temp: isothermal

no heat transfer: adiabatic

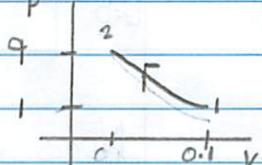
2.17



relationship for this gas is $pV^2 = \text{constant}$

$$p_1 = 1 \text{ bar}, V_1 = 0.1 \text{ m}^3, p_2 = 9 \text{ bar}$$

$$V_2 = 0.033$$



$$W = \int_{V_1}^{V_2} p \cdot dV = p_1 V_1 \int_{V_1}^{V_2} V^{-2} dV = \frac{p_2 V_2 - p_1 V_1}{1 - 2}$$

$$= \frac{9 \cdot 10^3 \cdot 0.033 - 0.1 \cdot 1 \cdot 0^3}{-1} = -197 \text{ J}$$

Mechanical equivalent of heat

heat is movement/vibration of mechanical movement

$$1 \text{ cal} = 4.184 \text{ J}$$

raise temp of 1 g H₂O from 14.5°C to 15.5°C

$$1 \text{ BTU} = 1055.06 \text{ J} \quad \text{British thermal unit}$$

raise 1 lb of H₂O from 59.5°F to 60.5°F

Q: heat

$Q > 0$ when energy transferred from surr. \rightarrow syst

$Q < 0$ syst \rightarrow surr.

$$\Delta E = Q_{1-2} - W_{1-2} \rightarrow dE = dQ - dW, \frac{dE}{dt} = \dot{Q} - \dot{W}$$

$$\dot{q} = \frac{d\dot{Q}}{dA} : \text{Heat flux}$$

Enthalpy $H = U + pV$ ← thermal energy

$$P \quad | \quad W = \int pdV = p\Delta V$$

$$\Delta E = Q_{1-2} - W_{1-2}$$

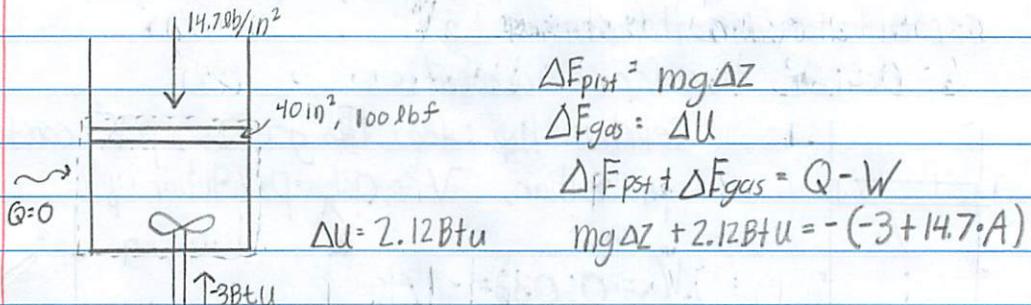
$$= Q_{1-2} - p\Delta V$$

$$Q_{1-2} = \Delta E + p\Delta V = \Delta H$$

if P is not constant

$$dH = dU + pdV + Vdp$$

2.49



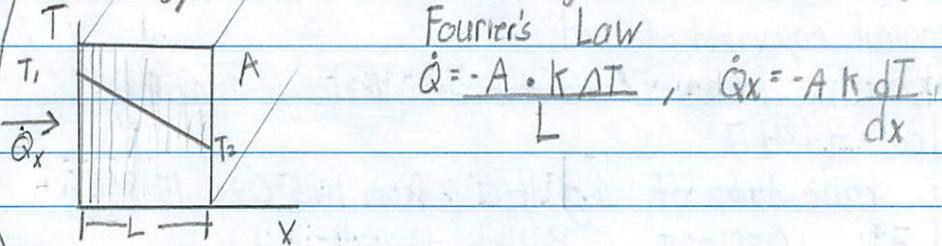
Modes of heat transfer

conduction:

Diff in temp is distributed by random motion of atoms

radiation:

energy is emitted by change in electron configuration



Stefan-Boltzmann Law: $\dot{Q}_e = A \sigma T_b^4$ ← ideal case

$$\sigma = 5.67 \cdot 10^{-8} = \epsilon A \sigma (T_b^4 - T_s^4)$$

↑ emissivity fraction
based on surface

Convection: mix of conduction with motion

Newton's law of cooling: $\dot{Q}_c = A h (T_b - T_f)$

↑ depends on flow condition

Nathan Stenseng

ME 2233

HW2

09/25/20

2.7

state 1

state 2

datum = 0 KJ

 $h=0$

900kg
0 0

 $h=50\text{m}$

900kg
0 0

 0 $v=0$

$$\tau = \overrightarrow{100 \text{ km/m}}$$

$$\Delta KE = \Delta \frac{1}{2} mv^2 = 0 - 900 \cdot 22.78^2$$

2

$$= -347 \text{ kJ}$$

$$\Delta PE = mg \Delta h =$$

441 kJ

2.19

a gas in a cylinder is compress. $pV^n = C$. $V_1 = 0.1 \text{ m}^3$. $V_2 = 0.04 \text{ m}^3$, $p_2 = 2 \text{ bar}$. Determine p_1 and W for $a. n=0$, $b. n=1$, $c. n=1.3$

$$a. p_2 \cdot V_2^0 = C = 2 \text{ bar} \cdot 1 = \frac{p=2 \text{ bar}}{V^0} = \frac{2 \cdot 10^5 \text{ N/m}^2}{1 \text{ m}^3}$$

$$W = \int_{0.1}^{0.04} \frac{2}{V} dV = 2(0.04 - 0.1) =$$

-12 kJ

$$p_1 = \frac{2}{1} = 2 \text{ bar}$$

$$b. p_2 \cdot V_2 = C = 2 \text{ bar} \cdot 0.04 \text{ m}^3 = 8 \text{ kJ} \quad P = \frac{8000}{V}$$

$$W = \int_{0.1}^{0.04} 8000/V dV = 8000 \ln(V) \Big|_{0.1}^{0.04} =$$

-7.3 kJ

$$P_1 = \frac{8000}{0.1} = 80000 \text{ Pa} = 0.8 \text{ bar}$$

$$c. p_2 V_2^{1.3} = C = 2 \text{ bar} \cdot 0.04^{1.3} \text{ m}^3 = 3.045 \text{ kJ} \quad P = \frac{3.045}{V^{1.3}}$$

$$W = \int_{0.1}^{0.04} 3.045 \cdot V^{-1.3} dV = 3.045 \cdot \frac{V^{-0.3}}{-0.3} \Big|_{0.1}^{0.04} =$$

-6.4 kJ

$$P_1 = \frac{0.03}{0.1^{1.3}} = 0.6 \text{ bar}$$

Energy Balance and Thermodynamic cycle overview

$$\Delta E = Q - W$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W} = \frac{dU}{dt} + \frac{dKE}{dt} + \frac{dPE}{dt}$$

assumptions:

if walls are poor conductors: $Q=0$

if nothing is on the system barrier: $W=0$

- no shaft or wires

steady state: $\frac{dE}{dt} = 0 = \dot{Q} - \dot{W} \therefore \dot{Q} = \dot{W}$

V is normally too slow and $KE = 0$

2.23

Nathan Stenseng ME 2233 Hw 2 09/25/20

Process 1-2:

$$\dot{W} = 0$$

Process 3-4:

$$\dot{W} = -400 \text{ kJ}$$

$$2.1 P_1 = 1.05 \cdot 4$$

Process 2-3:

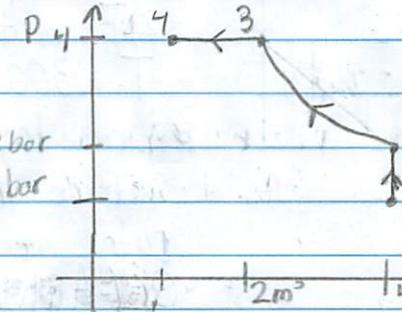
$$pV = C = 8 \text{ bar/m}^3$$

$$8 = p_3 V_3 = p_3 \cdot 2$$

$$p_3 = 4 \text{ bar}$$

$$\dot{W} = 2 \cdot 10^5 \cdot 4 \ln\left(\frac{2}{4}\right)$$

$$= -554 \text{ kJ}$$



2.26

A 0.15 m diameter pulley has Torque of 200 Nm applied and transmits 7 kW. Determine force on the pulley and RPM.

$$\dot{W} = 7,000 \text{ watts}$$

$$7,000 \cdot 200 \cdot \pi \cdot \text{Hz}$$

$$T = 200 \text{ N.m}$$

$$F = T/r$$

$$= 200/0.15 = 1333.33$$

$$= 1.33 \text{ kN}$$

$$\omega = 35 \text{ Hz}$$

$$= 2160 \text{ RPM}$$

2.47 a motor draws a current of 20 amps @ 110 V. $\omega = 2000 \text{ RPM}$

and $T = 9.07$. Determine \dot{W}_{in} , \dot{W}_{out} , the cost of

24 hours of operation if electricity is $0.09 \text{ \$/kWh}$

$$\dot{W} = E \cdot i$$

$$= 20 \cdot 110 = \dot{W}_{in} = 2000 \text{ W}$$

$$\dot{W}_{out} = T \cdot \omega$$

$$= 9.07 \cdot \frac{2000}{60} = 3023 \text{ W}$$

$$2 \text{ kW} \cdot 24 \text{ h} \cdot \frac{0.09 \text{ \$}}{\text{kWh}} = 4.32 \text{ \$}$$

2.51 A ridged 1 m³ tank has a paddle wheel transfer energy at a rate of 14 W/h. $\Delta U = 10 \text{ kJ/kg}$. There are 4 kg of gas

$$\text{a. specific } v = 0.25 \text{ m}^3/\text{kg}$$

$$\text{c. } \Delta U = Q - W$$

$$\text{b. } 14 = \frac{\text{work}}{1 \text{ h}} \Rightarrow 50.4 \text{ kJ}$$

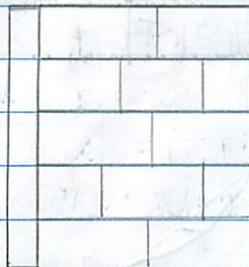
$$10 \text{ kJ} \cdot 4 \text{ kg} = Q - (-50.4)$$

$$\frac{\text{kg}}{Q = -10.4 \text{ kJ}}$$

2.36

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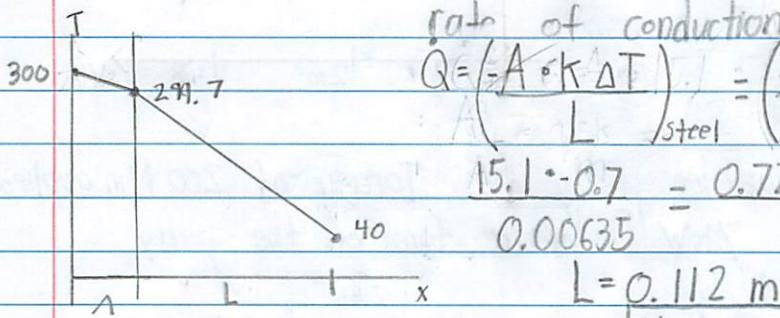
ME 2233 HW3



An oven wall consist of 0.635 cm steel layer, $K_s = 15.1 \text{ W/(m} \cdot \text{K)}$ and a brick layer, $K_b = 0.72 \text{ W/(m} \cdot \text{K)}$

ΔT over the brick layer = 0.7°C

$T_o = 300^\circ\text{C}$. How thick should the brick layer be to ensure the surface is 40°C . What is the rate of conduction too.



$$\frac{Q}{A} = -\frac{K \Delta T}{L} = \frac{(-A \cdot K \Delta T)}{L}_{\text{Steel}} = \frac{(-A \cdot K \Delta T)}{L}_{\text{Brick}}$$

$$\frac{15.1 \cdot -0.7}{0.00635} = \frac{0.72 \cdot (40 - 299.3)}{L}$$

$$L = 0.112 \text{ m}$$

$$\frac{\dot{Q}}{A} = -\frac{k \Delta T}{L} = \frac{1.66 \text{ kW}}{11.2 \text{ cm}} = \frac{1.66 \text{ kW}}{m^2}$$

2.41 The surrounding is at 47°C with $E = 0.93$, the convection coefficient at 27°C is $10 \text{ W/(m}^2\text{K)}$.

Determine the net heat transfer.

$$\frac{\dot{Q}}{A} = h(T_b - T_f) + E\sigma(T_b^4 - T_s^4) \quad \text{What is } T_s$$

$$-0.93 \cdot 5.67 \cdot 10^{-8} (T_b^4 - (47 + 273.15)^4) = 10 (T_b - (27 + 273.15))$$

$$-5.2731 \cdot 10^{-8} T_b^4 + 553.96 = 10 T_b - 3001.5$$

$$-5.2731 \cdot 10^{-8} T_b^4 - 10 T_b + 3555.462 = 0$$

$$T_b = 308.06 \text{ K or } -662.94 \text{ K}$$

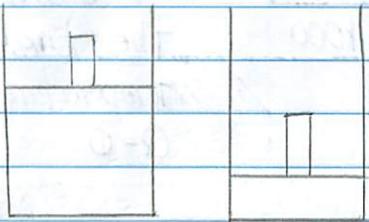
$$\frac{\dot{Q}}{A} = -0.711 \text{ kW/m}^2$$

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ME 2233

Hw 3

2.46



state 1

state 2

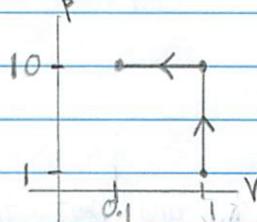
A gas in a piston-cylinder undergoes 2 processes, A and B, between the same end states, 1 and 2, where $p_1 = 1 \text{ bar}$, $V_1 = 1 \text{ m}^3$, $U_1 = 400 \text{ kJ}$ and $p_2 = 10 \text{ bar}$, $V_2 = 0.1 \text{ m}^3$

$$U_2 = 450 \text{ kJ}$$

Process A: isochoric from p_1 to p_2 and isobaric from V_1 to V_2

Process B: $pV = C$ from state 1 to 2

A



$$\begin{aligned} W &= P\Delta V = 10 \text{ bar} \cdot 0.9 \text{ m}^3 \\ &= 10 \cdot 10^5 \text{ N/m}^2 \cdot 0.9 \text{ m}^3 \end{aligned}$$

$$W = -900 \text{ kJ}$$

$$\Delta E = Q - W$$

$$50 \text{ kJ} - Q - (-900 \text{ kJ}) \quad \text{Sign?} \quad 50 \text{ kJ} = Q - (-230.26 \text{ kJ})$$

$$Q = -850 \text{ kJ}$$

$$\begin{aligned} W &= p_1 V_1 \ln(V_2/V_1) \\ &= 10^5 \text{ N/m}^2 \cdot 1 \text{ m}^3 \ln(0.1) \end{aligned}$$

$$W = -230.26 \text{ kJ}$$

$$\Delta E = Q + W$$

$$50 \text{ kJ} = Q + (-230.26 \text{ kJ})$$

$$Q = +180.26 \text{ kJ}$$

2.52

State	$P(\text{lbf/ft}^2)$	$V(\text{ft}^3/\text{lb})$	$U(\text{Btu/lb})$	Steam in a piston-cylinder undergoes a polytropic process. Determine work and heat transfer in Btu/lb of steam
1	14400	4.934	1136.2	
2	5760	11.04	1124.2	

$$p_1 V_1^n = p_2 V_2^n$$

$$\frac{\text{lbf}}{\text{ft}^2} \cdot \frac{\text{ft}^3}{\text{lb}} = \frac{\text{lbf} \cdot \text{ft}}{\text{lb}}$$

$$\ln(p_1 V_1^n) = \ln(p_2 V_2^n)$$

$$\frac{\text{lbf} \cdot \text{ft}}{\text{lb}} = 1 \text{ Btu}$$

$$\ln(p_1) + n \ln(V_1) = \ln(p_2) + n \ln(V_2)$$

$$778.17 \text{ ft} \cdot \text{lbf}$$

$$\ln(p_1) - \ln(p_2) = n(\ln(V_2) - \ln(V_1))$$

$$n = \frac{\ln(p_1/p_2)}{\ln(V_2/V_1)} = 1.138$$

$$W = p_2 V_2 - p_1 V_1 = 54162 \text{ lbf} \cdot \text{ft/lb}$$

$$W = 69.6 \text{ Btu/lb}$$

$$\Delta U = -12 = Q - W$$

$$Q = 57.6 \text{ Btu/lb}$$

2.53	state	$p(\text{lb}/\text{in}^2)$	$p(\text{lb}/\text{ft}^2)$	$V(\text{ft}^3/\text{lb})$	$T(^{\circ}\text{R})$	Determine
	1	100	14400	3.704	1000	the final
	2	50	7200	6.077		temperature!

$$\Delta U = (0.171)(T_2 - T_1), \quad pV^{1.4} = C \quad Q=0$$

$$14400 \cdot 3.704^{1.4} = 7200 \cdot V_2^n$$

$$V_2 = 6.077$$

$$W = \frac{p_2 V_2 - p_1 V_1}{1-n} = 23958 \text{ lbf} \cdot \text{ft/lb}$$

$$= 30.788 \text{ Btu/lb}$$

$$0.171(T_2 - 1000) = -30.788$$

$$0.171 T_2 = 140.21$$

$$T_2 = 819.96^{\circ}\text{R}$$

2.56 Determine the net work of the cycle, in kJ, and heat transfer in each process. Is it power or refrigeration.

process 1-2: isochoric, $V_1 = 2 \text{ m}^3$, $p_1 = 1 \text{ bar}$, $p_2 = 3 \text{ bar}$, $\Delta U = 400 \text{ kJ}$

$$400 \text{ kJ} = Q - W, \quad W = 0$$

$$Q = 400 \text{ kJ}$$

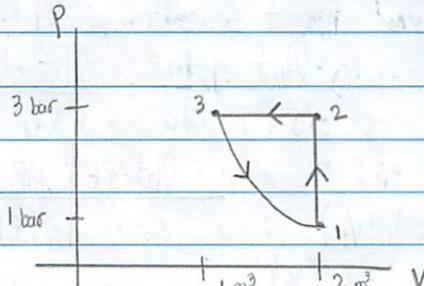
Process 2-3: isobaric, $V_3 = 1 \text{ m}^3$

$$W = p \Delta V = 3 \text{ bar} (1-2) \quad \Delta U = Q - W$$

$$W = -300 \text{ kJ} \quad \text{based on } 2-3: \Delta U = -250, \quad Q = -550 \text{ kJ}$$

Process 3-1: $Q = 0$, $W = 150 \text{ kJ}$

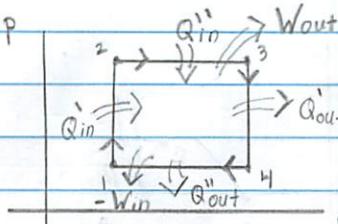
$$\Delta U = -150 \text{ kJ}$$



$$\sum W = -150 \text{ kJ}$$

This cannot be a power cycle because Work is (-) which means it is being done by the surrounding.

also $\Delta Q = -150 \text{ kJ}$ which means heat is lost which means it is a refrigeration cycle,



lowest temp @ 1
Highest @ 3

V Converts Heat \rightarrow Work

$$^* W_{4-1} = -W_{1-4}$$

$$\Delta E = \oint = Q - W \quad \therefore Q = W$$

closed cycle

$$\text{also } \dot{W} = \dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}$$

Thermo efficiency

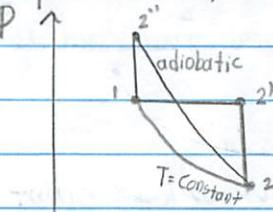
$$\eta = \frac{W_{\text{cycle}}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{1 - Q_{out}/Q_{in}}{Q_{in}} \quad \text{power cycle}$$

$$\beta = \frac{Q_{in}}{W_{\text{cycle}}} = \frac{Q_{in}}{Q_{out} - Q_{in}} \quad \text{refrigeration cycle}$$

$$\gamma = \frac{Q_{out}}{W_{\text{cycle}}} = \frac{Q_{out}}{Q_{out} - Q_{in}} = \frac{1}{1 - \frac{Q_{in}}{Q_{out}}} \quad \text{Heat pump}$$

$$\gamma = \beta + 1$$

chapter 3 Evaluating properties



$$v = \text{specific volume} = \frac{V}{m}$$

in order to keep something adiabatic
you actually need to add heat

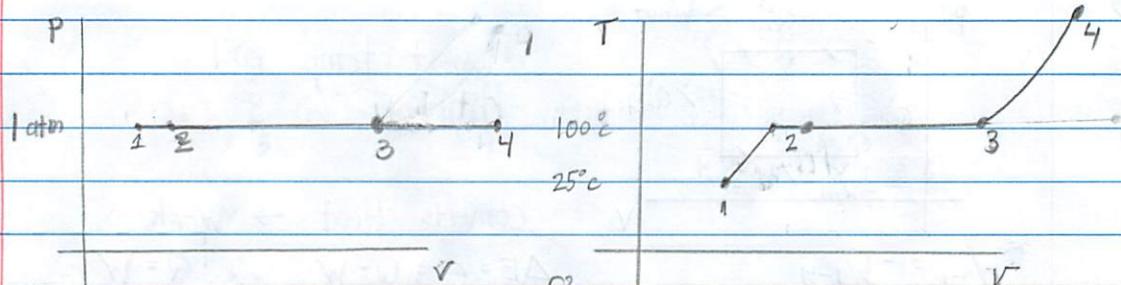
• A simple system has no internal boundary or external forces

- composite system: two parts of a system interact.
- degrees of freedom: $r+1$, r = number of work interactions
- simple compressible system: work by change in volume
- intensive state (value/mass) is completely defined by 2 independent properties

phase

• a quality of matter that is completely homogeneous
pure substance

- homogeneous only chemically, even if multiple chemicals as long as they are evenly distributed.



$$\Delta U = Q - p \int dV$$

$$H = Q = U + pV$$

enthalpy: latin for "to heat"

$$pV = mRT \rightarrow pV = RT$$

1-2: add heat

2-3: phase transition

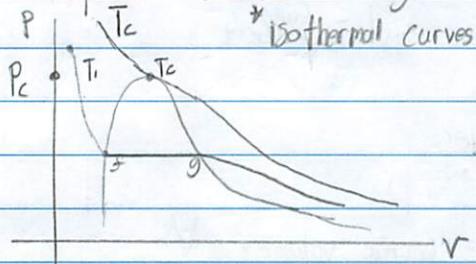
3-4: keep adding heat

latent heat: $h_{sg} = h_g - h_f$

g: gas

f: fluid in german means liquid

The p-v and T-v diagrams of pure substances



Vapor dome,

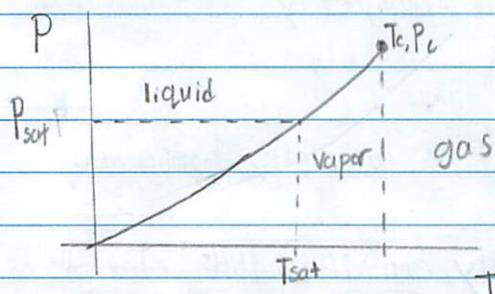
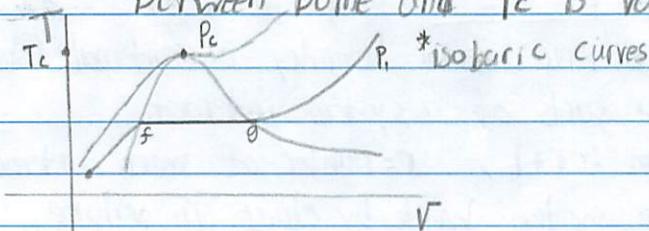
shows difference between supercritical fluids and not

left of curve is liquid

sub and super criticle above and below point.

Right of curves is gas

Between Dome and T_c is vapor



Quality:

exist only for a saturated substance

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

$$m_{\text{liquid}} + m_{\text{vapor}}$$

example:

$$U = U_e + U_g = U_{\text{imix}} + U_{\text{vapor}} = (1-X)U_e + XU_v \\ = X(U_v - U_e) + U_e$$

example: A 2-phase mixture of water at 6°C and $X=0.4$

Determine r in m^3/kg

$$\text{see table A-2: } V_f(6) = 1.0001 \cdot 10^{-3}$$

$$V_g(6) = 137.734$$

$$r = 0.4(137.734 - 1 \cdot 10^{-3}) + 1 \cdot 10^{-3} \\ = 55.094 \text{ m}^3/\text{kg}$$

Superheated Vapor:

$$T > T_{\text{sat}}, \quad P > P_{\text{sat}}$$

interpolation

$$y = m(X - x_1) + y_1$$

specific heat: change in energy per change in temp

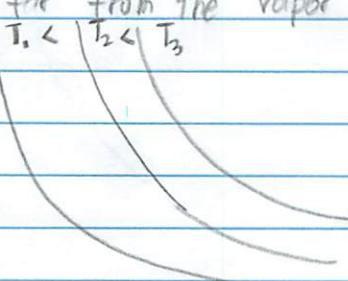
$$C_r = \frac{\partial u(T, r)}{\partial T} \Big|_{r=\text{const}} \quad \text{or} \quad C_p = \frac{\partial h(P, r)}{\partial T} \Big|_{P=\text{const}}$$

$$K = \frac{C_p}{C_r}$$

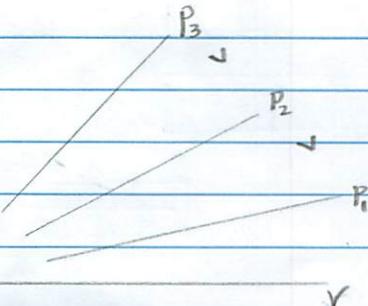
Ideal gas:

superior from the vapor dome

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



$$V \propto T$$



for ideal gasses: $U = U(T)$, only defined by T

$$h = U + PV = U(T) + RT$$

$$h = Q \text{ at constant pressure}, h = U + P\Delta V$$

constant V

constant P

$$PV = RT$$

$$C_V = \frac{du}{dT}, \quad C_P = \frac{dh}{dT} = \frac{du}{dT} + \frac{dRT}{dT} = C_V + R$$

example: $\Delta E = Q - W$

$$F-2 \quad 0 \quad 0 \quad -200 \quad -200$$

$$2-3 \quad 400 \quad 1000 \quad 600$$

$$3-4 \quad -1200 \quad 0 \quad 1200$$

$$4-1 \quad 800 \quad 800 \quad 0$$

Specific heat for an ideal gas.

• for ideal gas

$$u(T), \quad h(T)$$

$$\star \bar{C}_P = \bar{C}_V + \bar{R} \star \quad \bar{R} = 8.314 \text{ kJ/mol} \cdot K$$

$$du = C_V(T) dT, \quad R = \bar{R}/M_{\text{mass}}$$

$$\Delta U = \int [C_V(T)] dT$$

$$\text{if } C_V(T) = \text{const.} \quad \Delta U = C_V(T_2 - T_1)$$

$$\text{also: } \Delta h = \int [C_P(T)] dT$$

$$\text{if } C_P \text{ is constant, } \Delta h = C_P(T_2 - T_1)$$

$$\frac{C_P}{C_V} = K \Rightarrow C_P = K C_V \quad * K > 1$$

$$K C_V = C_V + R \Rightarrow C_V = \frac{R}{K-1}, \quad C_P = \frac{KR}{K-1}$$

For polytropic process

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

for ideal gas: $PV = RT$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{1-\frac{1}{n}}$$

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

also for ideal gas: when $n=1=k$

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

for $k=n \neq 1$

$$W = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Compressibility factor: how close to an ideal gas

$$z = \frac{RT}{PV} = 1 \text{ only use ideal for } 1 > z_c > 0.95$$

Reduced values

$$P_R = \frac{P}{P_c} \quad T_R = \frac{T}{T_c}$$

P_R and T_R are true for all substances

$$V_R = \bar{V} / \left(\frac{RT_c}{P_c}\right)$$

Compressed (subcooled) mixture

pressure or anything else doesn't change anything
only thing that matters is temperature

$$v(T, P) \approx v(T)$$

same with u and h

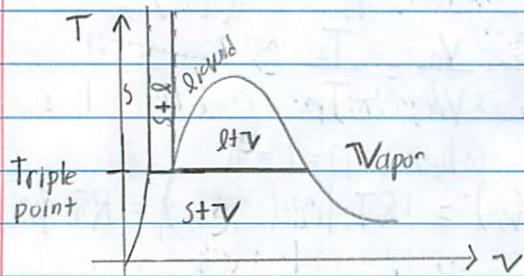
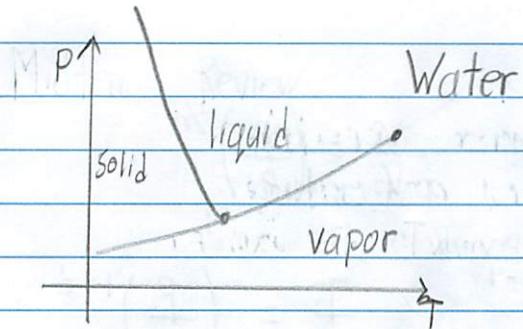
incompressible: only liquid and solid

no change in volume, \therefore no work

only change in pressure / a constant

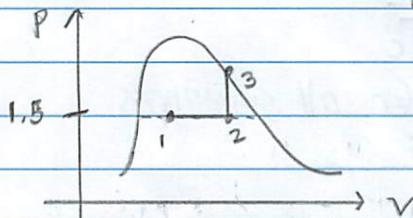
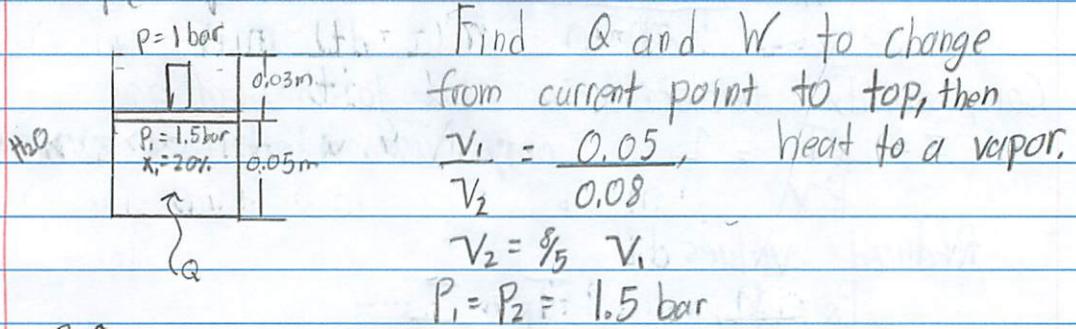
$$C = \frac{dU}{dT} = \frac{db}{dT}$$

$$h = u + \overbrace{pv}^{\text{constant}} \quad \frac{dh}{dT} = \frac{du}{dT} + 0$$



example problem

3.51



State	P	T	x	V	μ	h
1	1.5	111.4	0.2	0.033	877.5	912.4
2	1.5	111.4	0.37	0.052	1123.8	1179.6
3	~5	~159.2	1	0.072	~2561	~2749

$$W_{1-2} = P \Delta V = 150 \frac{\text{kN}}{\text{m}^2} \cdot (0.139) \frac{\text{m}^3}{\text{kg}} = 20.85 \frac{\text{kJ}}{\text{kg}}$$

$$q_{1-2} = h_2 - h_1 = 288.34 \frac{\text{kJ}}{\text{kg}}$$

chapter 4 Open systems:

closed system: no mass entering or exiting

open system: mass entering and exiting

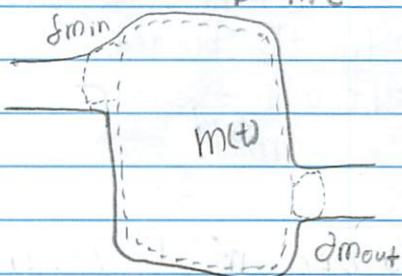
passes through the boundary

conservation of mass:

- mass is not created or destroyed

- this is actually just an engineering approximation

- $E = mc^2 \leftarrow$ mass destroyed and made to energy



small mass going in = mass going out

$$m(t) = m(t+dt)$$

$$\Delta m_{in} + m(t) = m(t+dt) + \Delta m_{out}$$

$$m(t+dt) - m(t) = \Delta m_i - \Delta m_o$$

$$\frac{\Delta m}{\Delta t} \quad \frac{dt}{dt} \quad \frac{dt}{dt}$$

formal def of derivative

$$\frac{\Delta m_i}{\Delta t} = \dot{m}_i \quad \frac{\Delta m_o}{\Delta t} = \dot{m}_o \quad \text{mass flow rate } \frac{\text{kg}}{\text{s}}$$

$$\frac{dm_{\text{system}}}{dt} = \sum \dot{m}_{\text{inlet}} - \sum \dot{m}_{\text{exit}}$$

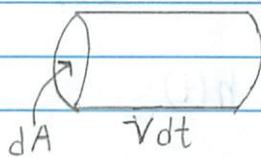
steady-states:

all properties are constant in Δt

$\sum \dot{m}_i = \sum \dot{m}_o$, but this does not mean

steady state is occurring

normal velocity



$$\text{Volume} = v_n dt dA_i$$

$$\Delta m = \rho v_n dt dA$$

$$\dot{m} = \rho v_n dA$$

$$m = \rho V$$

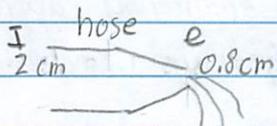
$$\frac{\dot{m}}{dA} = \rho v_n \quad \text{mass flux}$$

$$\frac{d}{dt} \int p dV = \sum \int_{A_i} p v_n dA_i - \sum \int_{A_e} p v_n dA_e$$

one dimensional approximation:
all properties are constant
boundaries are normal to the boundary
 $m = \rho A v$

$$\dot{m} = \rho \dot{V} \quad \dot{V} = A v \quad \text{also } \rho = \frac{1}{v} \quad v \text{ spec volume}$$

ex:



at 20°C , it takes 50 sec to fill the bucket.

$$\rho = 1,000 \frac{\text{kg}}{\text{m}^3}$$

$$\dot{m}_{\text{final}} = \rho \cdot V_f$$

$$\dot{V} (\doteq \frac{V}{\Delta t}) = 0.757 \text{ L/s}$$

$$\dot{m}_i = \frac{dm}{dt} = \rho \dot{V}$$

$$\dot{m} = \rho A v$$

$$\dot{V} = A v_e$$

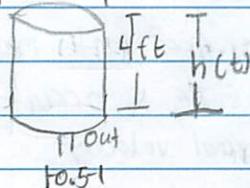
$$v_e = 15.1 \text{ m/s}$$

$$A_i v_i = A_e v_e$$

$$v_e = 2.42 \text{ m/s}$$

ex:

1-3 ft -1



$$v_{\text{out}} = \sqrt{2gh}. \text{ How long to go from } h(0) = 4 \text{ ft to } h(t) = 2 \text{ ft.}$$

$$\frac{dm}{dt} = -m_e = -\rho \left(\frac{\pi}{4} 3^2 \cdot h(t) \right)$$

$$m_e = -\rho \frac{\pi}{4} 3^2 h(t)$$

$$\rho A_e v_e = \dot{m}_e = -\rho \frac{\pi}{4} 3^2 \frac{dh(t)}{dt}$$

$$\int_{t_0}^{t_f} dt = \frac{-3^2}{0.5^2 \sqrt{2g}} \cdot \int_{4}^2 \frac{dh}{\sqrt{h}}$$

$$t_{\text{final}} = \frac{-3^2}{0.5^2 \sqrt{2g}} \cdot 2 \left[\sqrt{h} \right]_4^2 = 757 \text{ sec} = 12.6 \text{ min}$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}_i \left(u_i + \frac{V_i^2}{2} + g z_i \right) - \dot{m}_e \left(u_e + \frac{V_e^2}{2} + g z_e \right)$$

internal energy
of flowing mass

KE PE

$$\dot{W} = \dot{W}_{cv} + \dot{W}_{\text{boundary}} \quad \begin{matrix} \leftarrow \\ \text{control volume} \end{matrix} \quad \begin{matrix} \leftarrow \\ \text{flow work} \end{matrix}$$

\leftarrow From flow pushing mass in/out

$$\dot{W}_e = F_e V_e = P_e A_e V_e = P_e \dot{V}_e = \dot{m}_e (P_e V_e)$$

specific volume

$$\dot{W}_i = F_i V_i = P_i A_i V_i = P_i \dot{V}_i = \dot{m}_i (P_i V_i)$$

\checkmark system to surrounding

$$\dot{W} = \dot{W}_{cv} + \dot{W}_e - \dot{W}_i \quad \begin{matrix} \leftarrow \\ \text{surr onto system} \end{matrix}$$

$$\begin{aligned} \frac{dE}{dt} &= \dot{Q}_{cv} - \dot{W}_{cv} - \dot{W}_e + \dot{W}_i + \dot{m}_i (u_i + \frac{V_i^2}{2} + g z_i) - \dot{m}_e (u_e + \frac{V_e^2}{2} + g z_e) \\ &= \dot{m}_e (P_e V_e) - \dot{m}_i (P_i V_i) \\ &= \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i (P_i V_i + u_i + \frac{V_i^2}{2} + g z_i) - \dot{m}_e (P_e V_e + u_e + \frac{V_e^2}{2} + g z_e) \\ &\quad * P_i V_i + u_i = h_i \end{aligned}$$

$$\star = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_e (h_i + \frac{V_i^2}{2} + g z_i) - \dot{m}_e (h_e + \frac{V_e^2}{2} + g z_e) \star$$

at steady state:

$$\frac{dE}{dt} = 0, \quad \text{if 1 inlet and outlet}$$

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

ex: 3 ft diameter tank, open to 20°C atmosphere. Nozzle of 0.5 in diameter at the end.

$h = z_T - z_J$

$\checkmark D_T$ $\checkmark D_J$ \checkmark height

Tank \checkmark $\dot{m} = \rho V_T \frac{\pi D_T^2}{4}$

Jet \checkmark $\dot{m} = \rho V_J \frac{\pi D_J^2}{4}$

$\rho V_T \frac{\pi D_T^2}{4} = \rho V_J \frac{\pi D_J^2}{4}$

$V_T = \frac{D_J^2}{D_T^2} V_J \approx 0$

1 atm $\checkmark 0$ 1 atm

$$P_T + \rho g z_T + \rho V_T^2/2 = P_J + \rho g z_J + \rho V_J^2/2$$

$$V_J = \sqrt{2gh}$$

Air steady state flow in a pipe at 300 kPa, 350 K, and 25 m/s, at rate of 18 kg/min find diameter of pipe, rate of flow of energy, rate of energy transferred by mass

Air →

\dot{m}_L

\dot{m}_E

$$\dot{m}_L = \dot{m}_E = \frac{18 \text{ kg}}{\text{min}} = 0.3 \frac{\text{kg}}{\text{s}}$$

$$P_v = RT$$

$$P \cdot \frac{1}{\rho} = RT$$

$$P = \frac{P}{RT}$$

$$R = 0.287 \text{ kJ}$$

$$\text{kg} \cdot \text{K}$$

of air

$$P = 0.335 \frac{\text{m}^3}{\text{kg}}$$

$$\star \quad \dot{m} = \rho A V_{\text{er}} \quad \star$$

$$0.3 = 0.335 A \cdot 25$$

$$A = 4.02 \cdot 10^{-3}$$

$$\therefore D = 7.15 \cdot 10^{-2} \text{ m}$$

$$W_C = \dot{m}_L P_C V_C = 0.3 \cdot 300 \cdot 0.335 = 30.15 \text{ kW}$$

Transient Analysis of the mass balance

$$\frac{d m_{cv}}{dt} = \sum \dot{m}_L - \sum \dot{m}_E$$

You can find total mass i.e from $t_1 \rightarrow t_2$

$$m_{cv}(t_2) - m_{cv}(t_1) = \sum \dot{m}_L - \sum \dot{m}_E$$

also you can integrate E equation

$$E_{cv}(t_2) - E_{cv}(t_1) = (Q_{cv} - W_{cv} + \sum m_i h_i - \sum m_e h_e)$$

$$(U_{cv}(t_2) - U_{cv}(t_1))$$

PE and KE are negligible on both sides.

A rigid, insulated tank vacuum is connected to a steam pipe at 1 MPa and 300°C. Steam flows into the tank until pressure = 1 MPa.

Determine the final temp of steam in tank cv.

$$U_{cv}(t_2) - U_{cv}(t_1) = Q_{cv} - \cancel{W_{cv}} + m_i h_i - m_e h_e$$

$$\mu_u = U \quad \rightarrow \quad \rightarrow \quad \rightarrow \text{Steam}$$

$$m_{cv}(t_2) U_{cv}(t_2) = m_i h_i \quad \leftarrow \text{Valve}$$

$$m_{cv} = m_i$$

$$h_i = U_{cv}(t_2)$$

$$U_{cv}(t_2) = h_i(10 \text{ bar}, 300^\circ\text{C}) = 3051.05 \text{ kJ/kg}$$

$$U_{cv}(t_2) (10 \text{ bar}, T_2) = 3051.05 \text{ kJ/kg}$$

$$T_2(t_2) = 456.3^\circ\text{C}$$

Adiabatic Process : $Q_{cv} = 0$

- Outer surface is well insulated
- temp between syst and surr is small
- outer surface area is too small to transfer heat
- not enough time given to let heat transfer

Negligible Work: Power : $W_{cv} = 0$

- No rotating shafts crossing system boundary
- No moving surfaces at system boundary
- No electrical wires or magnetic fields crossing boundary

Negligible PE : $\rho g \Delta z \ll \Delta U$

Negligible KE: Normally when temp is not constant $\Delta U \gg \Delta KE$
Steady state in real life

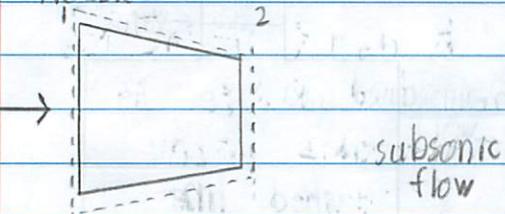
Many component work constantly non-stop like in a power plant. We can use idealization of steady-state flow here.

Chapter 4 Idealized Engineering Devices

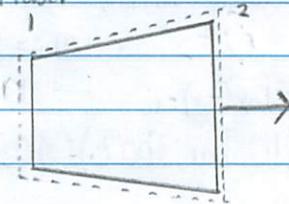
Nozzles and diffusers

devices providing a duct of varying cross-sections area which is purposely shaped to cause large changes in fluid velocities and thus KE.

Nozzle



Diffuser



$$V_{el\ 2} > V_{el\ 1}$$

$$P_2 < P_1$$

$$h = P_v + u$$

$$V_{el\ 2} < V_{el\ 1}$$

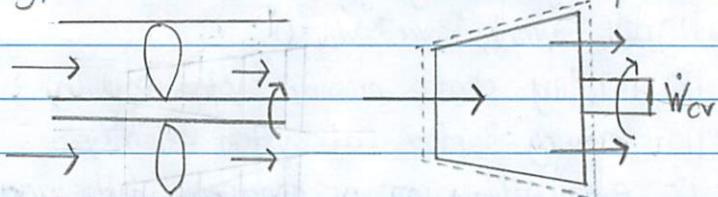
$$P_2 > P_1$$

$$\dot{Q}_{cv} - \dot{W}_{cv} + m [(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)] = 0$$

$$(h_2 - h_1) + \frac{(V_2^2 - V_1^2)}{2} = 0$$

Turbine:

turns energy rate (\dot{E}) into mechanical power



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

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

Compressors, pumps, and fans:

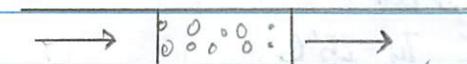
opposite of turbine, but same equation

mechanical power to increase energy rate

throttling devices:

Cheap and effective devices that lower pressure

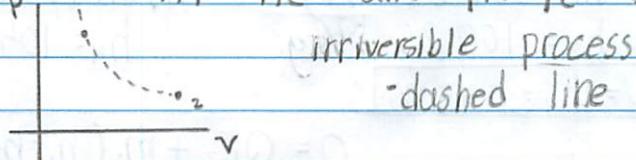
Static devices



porous plug

$$\dot{Q} = \dot{m}(c_v - w_{cv}) + m((h_1 - h_2) + \frac{1}{2}(V_1^2 - V_2^2) + g(z_1 - z_2))$$

$$h_1 = h_e \text{ and } p_i > p_e \star$$



$$p_1 V + U_1 = p_2 V + U_2 \quad *U(P,V)$$

ex: R-134a: determine x_2 after the throttling device.

$$h_1 = h_2$$

$$x_1 = 0$$

$$p_1 = 8 \text{ bar}$$

$$x_2 = ?$$

$$p_2 = 1.2 \text{ bar}$$

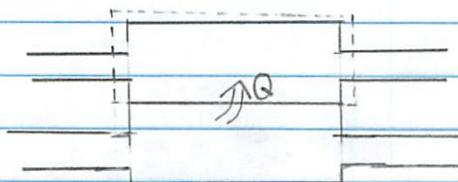
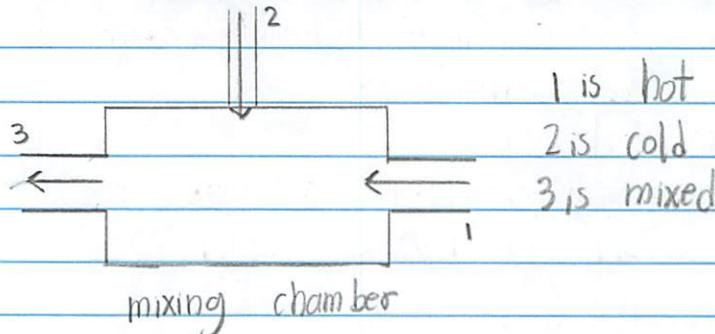
$$\therefore h_1 = 93.42 \text{ kJ/kg} \Rightarrow h_2$$

$$93.42 = x_2(h_{fg}(1.2 \text{ bar}) + h_f(1.2 \text{ bar}))$$

$$x_2 = 0.339$$

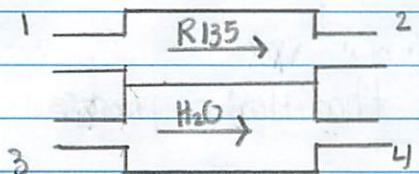
heat exchanger

• transfer heat from one fluid to another



$$\dot{Q} = \dot{m}_1(h_1 - h_2)$$

ex



$$\dot{m}_1 = \dot{m}_2 = 6 \text{ kg/min} = 0.1 \text{ kg/s}$$

$$P_1 = 10 \text{ bar} \quad T_1 = 70^\circ\text{C}$$

$$x_2 = 0 \quad T_2 = 36^\circ\text{C}$$

$$P_3 = P_4 = 3 \text{ bar}$$

$$T_3 = 15^\circ\text{C} \quad T_4 = 25^\circ\text{C}$$

Determine \dot{Q}_{1-2} and \dot{m}_3/\dot{m}_4

$$\star \sum m_i h_i = \sum m_e h_e \star$$

✓ because liquid

$$\text{Table: } h_1 = 302.24 \text{ kJ/kg}$$

$$h_3(P, T) = h_{fg}(T) = 62.99 \text{ kJ/kg}$$

$$h_2 = 100.25 \text{ kJ/kg}$$

$$h_4 = 104.89 \text{ kJ/kg}$$

$$\dot{m}_3 = \dot{m}_4 = 0.482 \text{ kg/s}$$

$$Q = \dot{Q}_{1-2} + \dot{m}_1(h_1 - h_2)$$

$$\dot{Q}_{1-2} = -20.2 \text{ kW}$$

ex

$$\text{compressor: } P_1 = 100 \text{ kPa} \quad T_1 = 280 \text{ K}$$

$$P_2 = 600 \text{ kPa} \quad T_2 = 400 \text{ K}$$

$$\dot{m} = 0.02 \text{ kg/s} \quad q_{1-2} \text{ loss} = 16 \text{ kJ/kg. Determine } \dot{W}_{cv}$$

$$Q = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

$$280.13 \xrightarrow{\sim} 400.98 \quad \dot{Q}_{cv} = q \cdot \dot{m} \\ = 16 \cdot 0.02$$

$$\dot{W}_{cv} = -2.737 \text{ kW}$$

The Second law of thermodynamics

- experience tells us nothing is natural reversible

- 2nd law

- says if a process can occur and which direction it occurs

- irreversible process example

- heat transfer hot \rightarrow cold

- friction

- gas expansion to a lower pressure

- mixing of 2 gas

- we can bring these systems back to the original state but we need to put in work

- internal irreversibility

- occurs within the system

- external irreversibility

- occurs outside the systems

- internally reversible

- quasi-static/quasi equilibrium process

2nd law

- also tells us the equilibrium state conditions

- a system will tend to the most probable configuration

3 definitions

- entropy statement: Just the number in the table

- clausius statement: heat goes from hot \rightarrow cold

- kelvin-Plank statement:

- We can't prove 2nd law, but it is observed in every thing we have seen so far.

1st law

$$\Delta U = Q - W$$

$$dU = \partial Q - \partial W \quad \leftarrow \text{when internally reversible}$$

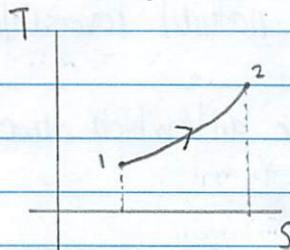
$$dU = TdS - pdV$$

↑ force ↓ displacement

$$ds = \left(\frac{dU}{T} \right)_{\substack{\text{constant} \\ \text{volume}}} = \frac{\partial Q}{T}$$

$$\uparrow W=0 \quad \uparrow P \quad \downarrow v$$

T-S diagram



$$Q = \int_1^2 T dS \quad \text{area under the curve}$$

2nd law

- entropy of the universe is always increasing
order \rightarrow chaos

$$\Delta S_{\text{cold}} = \frac{Q}{T_{\text{cold}}} \quad \Delta S_{\text{hot}} = -\frac{Q}{T_{\text{hot}}}$$

Thermal reservoir

a reversible system which remains at constant temp
regardless of the amount of energy transferred

$$\Delta S = \Delta S_c + \Delta S_H = Q \left(\frac{1}{T_c} - \frac{1}{T_H} \right) = 0$$

Kelvin plank statement

2nd law

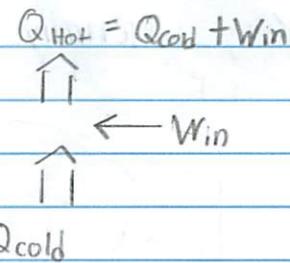
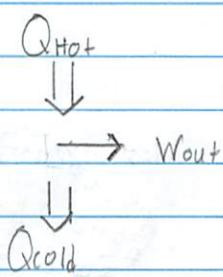
- it is impossible for any system to operate in a thermo cycle and deliver a net amount of energy by work to the surrounding while receiving energy by heat transfer from a single thermo reservoir
- a cycle needs 2 reservoirs at different temps

V	P	T_c	T_h	$P/2$	$2V$
		0°C		0°C	
		100°C		0°C	
		9°C		0°C	
		0°C		0°C	

only travels in this path

must go $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 1$
Never $1 \rightarrow 2, 2 \rightarrow 1$

never go from state $2 \rightarrow 1$ without another source



$$Q_{\text{cold}} \neq 0; \text{ Kelvin-Planck}$$

$\therefore \max \eta \leq 1$

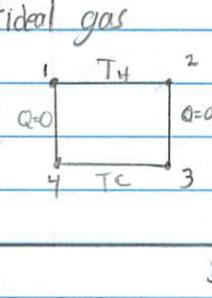
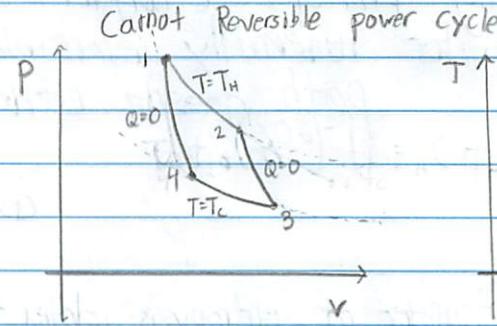
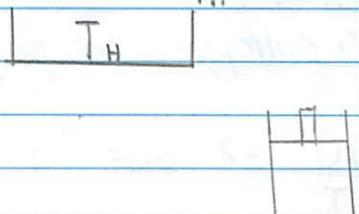
$$\eta = \frac{(W_{\text{cycle}})}{(Q_H)_{\text{rev}}} = 1 - \frac{(Q_c)}{(Q_H)} = 1 - \frac{\Psi(T_c, T_H)}{Q_H} \quad \text{only ratio: } \frac{Q_c}{Q_H} = \frac{T_c}{T_H}$$

Absolute thermodynamic temp:

ability for a body to give heat

high temp gives lots of heat

$$\eta_{\text{rev}} = 1 - \frac{T_c}{T_H}$$



Reversible processes:

only isothermal and adiabatic processes

1-2, isothermal expansion; 2-3 adiabatic expansion; 3-4 isothermal compression; 4-1 adiabatic compression

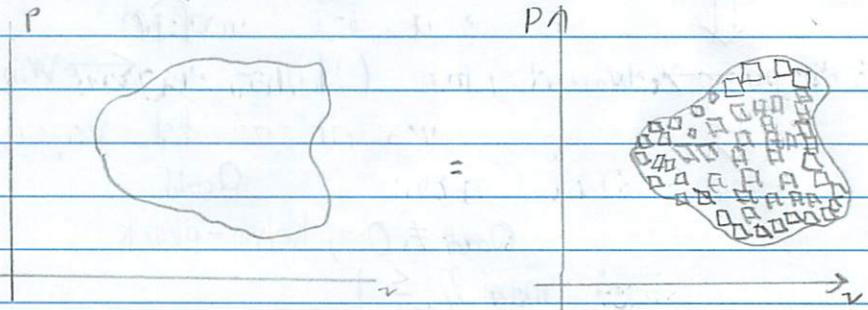
\nwarrow using T_H

\nearrow using T_c

$$* ds = \frac{dQ}{T}$$

if $dQ=0$, $ds=0$

Arbitrary internally reversible cycles:



a cycle can be approximated as a bunch of carnot cycles

$$\sum_{\text{cycles}} \frac{Q_i}{T_i} \leq 0 \Rightarrow \int \frac{dQ_i}{T_i} = -\Omega_{\text{cycle}} \leq 0$$

↑ entropy generation

$$\Omega > 0 \quad \Omega = 0 \quad \Omega < 0$$

Irreversible reversible impossible

Using Entropy chapter 6

For Internally reversible processes:

path doesn't matter \therefore entropy is a property

$$S_2 - S_1 = \int^2_1 (\partial Q/T)_b + \Omega$$

$$ds = \frac{\partial Q}{T} \Rightarrow \partial Q = Tds$$

a transfer of entropy is related to transfer of heat

$$Q = \int \partial Q = \int Tds \quad \text{same as } W = \int pdV$$

$$dU = \partial Q - \partial W$$

$$\text{Gibbs: } Tds = du + pdv$$

$$* h = u + pv \quad \text{product rule}$$

$$dh = du + d(pv)$$

$$dh = du + vdp + pdv$$

$$Tds = dh - vdp$$

at constant pressure, $vdp = 0$

$$Tds = dh$$

abscissa: adiabatic and reversible
 verticle on a T-s diagram
 enthalpy-entropy diagram (Mollier) diagramme
 used for large quality or saturated vapor
 incompressible fluid entropy

- constant p , constant v
- only function of T
- $du = c_v dT$, $dh = c_p dT + v dp$ often $c_v(T)$ is constant
- $ds = \frac{c_v}{T} dT$ $\Delta s = \int_{T_1}^{T_2} \frac{c_v(T)}{T} dT$
- $$\boxed{s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right)}$$

Ideal gas:

low pressures and high temperatures

$$pv = RT \quad u(T) = \int c_v(T) dT \quad h(T) = \int c_p(T) dT$$

\nwarrow constant $v \quad \nwarrow$ constant P

$$TdS = du + pdv \\ = c_v dT + \underbrace{RT}_{P} dv$$

$$dS = \int C_v \frac{dT}{T} + R \int \frac{dv}{P} = \int C_v \frac{dT}{T} + R \ln\left(\frac{v_2}{v_1}\right)$$

$$TdS = dh - pdv \\ = c_p dT - \underbrace{\frac{RT}{P} dP}_{pdT} = \int c_p(T) \frac{dT}{T} - R \ln\left(\frac{P_2}{P_1}\right)$$

\nwarrow table A-40: s°

$$s^\circ(T) = \int c_p(T) \frac{dT}{T}$$

$$\boxed{\Delta S = \Delta S^\circ(T) - R \ln\left(\frac{P_2}{P_1}\right)}$$

if $c_p(T) \approx c_p$ $c_v(T) = c_v$

$$\Delta S = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right), \quad \Delta S = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right)$$

Tsen tropic process: ideal reversible adiabatic devices

$\Delta S = 0$, vertical T-s line

$$\Delta S = 0 = \Delta S^o(T) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$0 = S^o(T_2) - S^o(T_1) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$\frac{P_2}{P_1} = \frac{P_{n2}(T_2)}{P_{n1}(T_1)}, \quad \frac{V_2}{V_1} = \frac{V_{n2}(T_2)}{V_{n1}(T_1)}$$

OPEN systems:

$$\frac{ds_{cv}}{dt} = \sum \frac{\dot{Q}}{T} + \sum \dot{m}_{ei} - \sum \dot{m}_{e\bar{s}} + \dot{o}_{cv}$$

steady state:

$$0 = \sum \frac{\dot{Q}}{T} + \sum \dot{m}_{ei} - \sum \dot{m}_{e\bar{s}} + \dot{o}_{cv}$$

$$\dot{m}_i = \dot{m}_{e\bar{s}}$$

$$0 = \sum \frac{\dot{Q}}{T} + \dot{m}(s_e - s_{e\bar{s}}) + \dot{o}_{cv}$$

adiabatic, no heat change

$$s_e - s_{e\bar{s}} = \dot{o}_{cv}/\dot{m}$$

internally reversible isothermal

$$q = \frac{\dot{Q}}{\dot{m}} = T(s_e - s_{e\bar{s}}) = \int_i^e T ds$$

recall:

$$q - w_{ext} (h_r - h_2) + (\nu_1^2/2 - \nu_2^2/2) + g(z_1 - z_2) = 0$$

$$\hookrightarrow T(ds) = dh - vdp = (h_r - h_2) - \int v dp$$

$$w_{ext} = - \int v dp + (\nu_1^2/2 - \nu_2^2/2) + g(z_1 - z_2)$$

$$w = - \int v dp$$

Open system

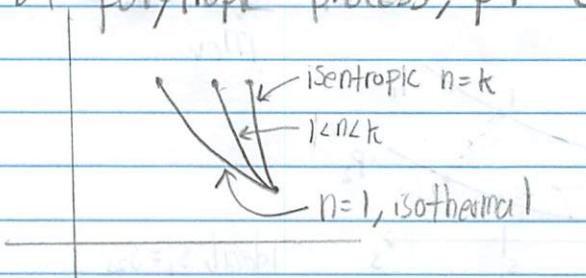
and $w = \int pdv$
closed system

Bernoulli Equation: $W_{ext} = 0$

$$\int_1^2 v dp + \left(\frac{v_2^2}{2} - \frac{v_1^2}{2}\right) + g(z_2 - z_1) = 0$$

if incompressible, v is constant

Work of polytropic process, $pv^n = C$, Open system!



isochoric $n \rightarrow \infty$, $W = -v \Delta P$

$$n \neq 1, W = -(P_2 v_2 - P_1 v_1) \quad n=1, W = -P_1 V_1 \ln\left(\frac{P_2}{P_1}\right)$$

isobaric, $n=0$, $W=0$

Ideal gas: $pv = RT$

$$\text{isothermal; } n=1 \quad W = -RT \ln\left(\frac{P_2}{P_1}\right)$$

$$n \neq 1, W = -\frac{n}{n-1} RT_1 \left(\frac{P_2}{P_1}^{\frac{n-1}{n}} - 1 \right)$$

$$n=k, \text{ isentropic}, W = -C_p(T_2 - T_1)$$

Work for an irreversible process:

$$\delta Q_{rev} - \delta W_{rev} = Tds - \delta W_{irr, rev} = \delta q_{irr} - \delta w_{irr}$$

$$\frac{\delta W_{rev} - \delta W_{irr}}{T} = ds - \frac{\delta q_{irr}}{T}$$

$$\frac{\delta q_{irr} + \delta w_{irr}}{T} \quad \therefore ds > \frac{\delta q_{irr}}{T}$$

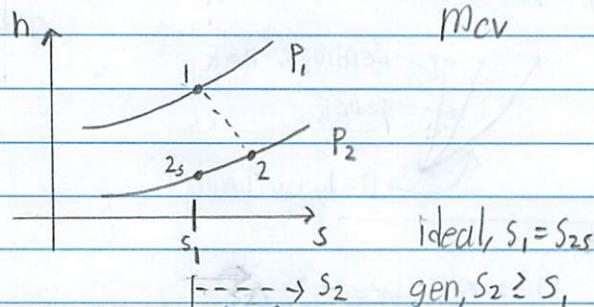
Real devices:

Turbine:

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

and $\dot{Q} = \sum \dot{Q}_T + \dot{m}(s_1 - s_2) + \dot{Q}_{cv}$

$$\therefore s_2 - s_1 = \frac{\dot{Q}_{cv}}{\dot{m}_{cv}} \geq 0$$



$$\text{ideal: } \dot{W}_{cv} = (h_1 - h_{2s})$$

$$\text{real: } \dot{W}_{cv} = \frac{\dot{m}}{\dot{m}} (h_1 - h_2) \quad \eta_t = \frac{\text{real}}{\text{ideal}} = \frac{h_1 - h_2}{h_1 - h_{2s}} \leq 1$$

often 0.8-0.9

nozzle:

$$(h_2 - h_1) + \frac{1}{2} (v_2^2 - v_1^2) = 0, \quad \dot{Q} = \dot{m}(s_1 - s_2) + \dot{Q}_{cv}$$

$$\eta_{\text{nozzle}} = \frac{v_2^2/2}{v_2 s_2/2}, \quad \frac{h_1 - h_2 + v_1^2/2}{h_1 - h_{2s} + v_1^2/2} \leq 1$$

Final review

Entropy generation in a throttling device

$$\begin{aligned} (h_1 - h_2) &= 0 & h_1 = h_2 \\ p_1 = 0.7 \text{ atm} & \quad T_1 = 280 \quad h_1 = 3035 \quad s_1 = 8.3162 \\ p_2 = 0.35 \text{ atm} & \quad h_2 = 3035 \quad s_2 = 8.6295 \\ \dot{Q} &= m(s_2 - s_1) + \dot{\Omega}_{cv} \\ \frac{\dot{\Omega}_{cv}}{m} &= 0.3132 \text{ kJ/kg K} \end{aligned}$$

check last
table in appendix
fig d.8

σ in a heat exchanger

water: $T_1 = 35^\circ\text{C}$ $m = 10,000 \text{ kg/h}$,

$$x_1 = 1 \quad x_2 = 0$$

air: $P_1 = 1 \text{ atm}$ $T_1 = 20^\circ\text{C}$

$$T_2 = 30^\circ\text{C} \quad P_2 = P_1$$

$$\dot{Q} = m_{\text{water}}(h_1 - h_2) + m_{\text{air}}(h_3 - h_4)$$

$$\therefore m_{\text{air}} = 673.3$$

$$m_{\text{water}}(s_1 - s_2) + m_{\text{air}}(s_3 - s_4) + \dot{\Omega} = 0$$

$$\approx s_3^\circ - s_4^\circ - R \ln \left(\frac{P_2}{P_1} \right)$$

$$\dot{\Omega} = 0.79 \text{ kW/k}$$

Isentropic nozzle efficiency

$$\text{air: } P_1 = 2 \text{ kPa} \quad T_1 = 960 \text{ K} \quad \alpha = 0 \quad V_r \downarrow$$

$$P_2 = 110 \text{ kPa} \quad \eta = 92\%$$

$$\eta = \frac{V_2^2/2}{V_{2s}^2/2}$$

since isentropic, $\Delta S = 0$, $P_r = 97.00$

$$P_{r2s} = P_{r1} (97) = 97$$

$$P_{r2s} = P_{r1} \left(\frac{P_2}{P_1} \right) = P_{r\text{air}} (823 \text{ k})$$

$$h_{2s} = 847.33 \text{ kJ/kg}$$

$$V_{2s} = 553.6$$

$$V_2 = 531.0 \text{ m/s}$$

Pump

$$\dot{m} = 1.2 \text{ kg/s} \quad H_2O(l) \quad T_f = 50^\circ\text{C} \quad P_1 = 1.5 \text{ MPa}$$

$$P_2 = 15 \text{ MPa}$$

$$\dot{W}_p = 21 \text{ kW} = \dot{m} w$$

ME 2233 Review

Helmholtz Equation of state:

Tables in the back of the book or software

Things that undergo phase change
water, R22 ...

We need 2 intensive independent properties
to fix the state

P and T are not independent during a phase change

liquid approximations

$$v(T, p) \approx v_f(T)$$

$$u(T, p) \approx u_f(T)$$

$$s(T, p) \approx s_f(T)$$

$$h(T, p) \approx h_f(T) + v_f(T)[p - p_{sat}(T)]$$

Incompressible model

$v = \text{constant}$, applies for many liquids and solids

Total gas

no phase change

$$pv = RT$$

$$u = u(T), \quad h = h(T)$$

$$c_v = \frac{du}{dT}, \quad c_p = \frac{dh}{dT}$$

$$\Delta u = \int_{T_1}^{T_2} c_v dT, \quad \Delta h = \int_{T_1}^{T_2} c_p dT$$

c_v and c_p can be constant for small ΔT
and monatomic gasses

Conservation equations

1. mass

$$\frac{dm_{cv}}{dt} = \sum m_{in} - \sum m_{out}$$

2. 1st law (NRG)

3. 2nd law (entropy)

$$\frac{dS_{cv}}{dt} = \sum \frac{Q_j}{T_j} + \sum m_{in} s_{in} - \sum m_{out} s_{out}$$

$$\frac{dE_{cv}}{dt} = Q_{cv} - W_{cv} + \sum m_i (h_i + \frac{V^2}{2} g z_i) - \sum m_o (h_o + V_o g z_o + g_o)$$

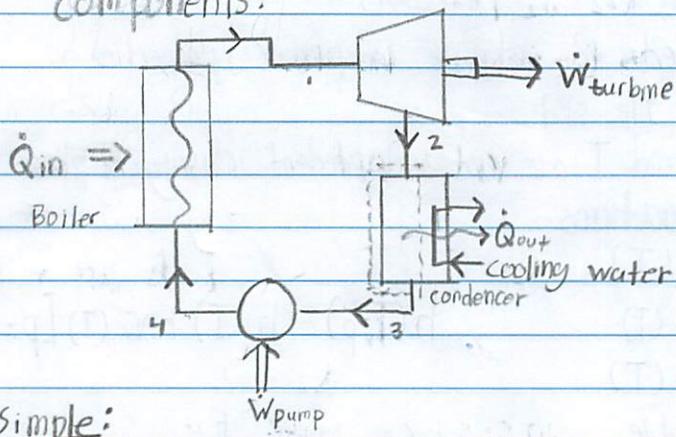
$$\frac{d}{dt} = 0 \text{ for all properties inside the cv at steady state}$$

Rankine Cycle: working fluids have a phase change
a subsystem to a powerplant

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

$$\dot{Q}_{in}/m$$

components:



Simple:

$$\text{Turbine: } \frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$$

$$\text{condenser: } \frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

$$\text{Pump: } \frac{\dot{W}_p}{\dot{m}} = h_3 - h_4$$

$$\text{Boiler: } \frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

feed water

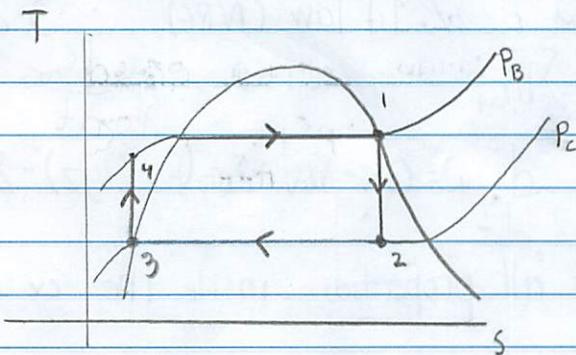
Ideal Rankine Cycle:

1-2 Turbine: Isentropic expansion from a saturated vapor to condenser pressure

2-3 Condenser: Isobasic condensation to a saturated liquid

3-4 Pump: Isentropic compression, subcooled liquid

4-1 Boiler: Isobasic evaporation to sat. vapor



Fixing state 4:

$s_3 = s_4$ and $p_1 = p_4$, do this with software
with tables:

$$h_4 \approx h_f(T_4) \text{ and } p_4 = p_1$$

best: water is incompressible

$$\frac{W}{m} = \int v dp = v_3 (p_3 - p_4) = h_3 - h_4$$

$$\therefore h_4 = h_3 + v_3 (p_4 - p_3)$$

Performance metric:

$$\eta = 1 - \frac{\dot{Q}_{out}/m}{\dot{Q}_{in}/m} \propto 1 - \frac{T_o}{T_i} \leftarrow \text{only use conceptually}$$

lowest temp:

cooling water $\approx 20^\circ C - 25^\circ C$ room temp

Increase boiler temp:

higher $P_b \Rightarrow$ higher T_{in}

We want high x in turbine so droplets don't break
the turbine

Inefficiencies in the Rankine Cycle:

internal:

pump and turbine inefficiencies

use isentropic efficiency to quantify

external:

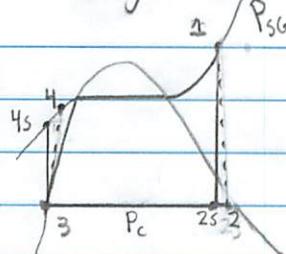
heat transfer, finite temp difference

Superheated Rankine cycle:

increase temp into turbine but same pressure

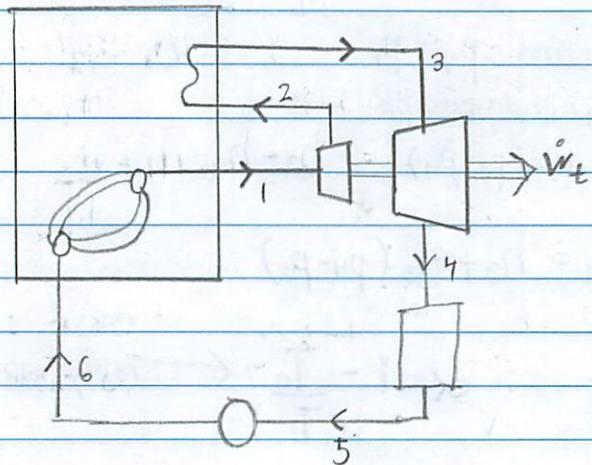
goes from sat. vapor to superheated vapor

Boiler changes to steam generator



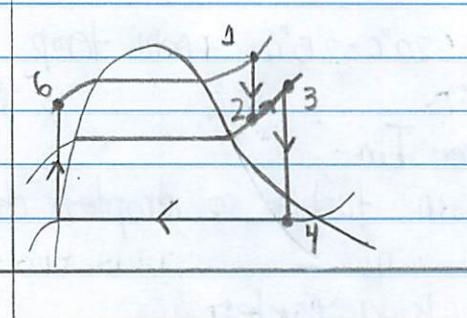
Reheat Rankine cycle:

Have 2 turbines: High pressure and low pressure



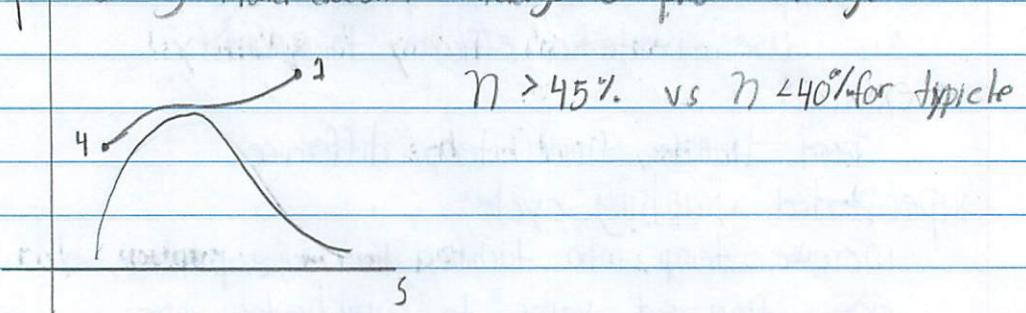
superheated generator
overheats fluid.

We go back in at
lower pressure and
use that heat



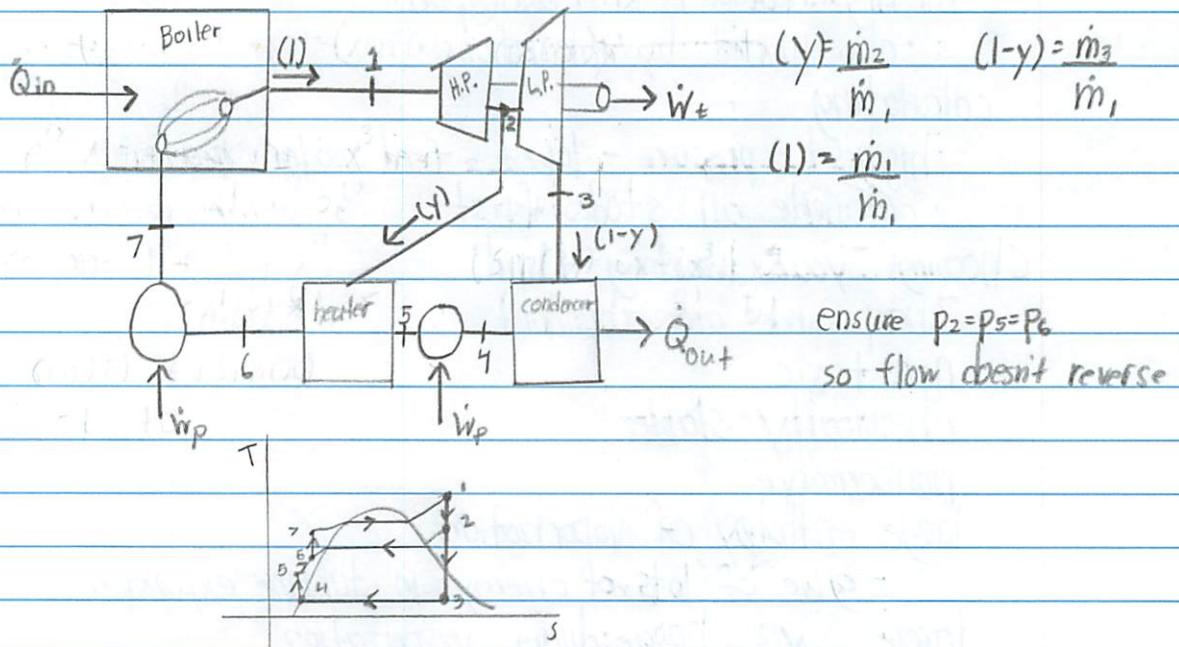
Supercritical Rankine cycle:

Working fluid doesn't undergo a phase change



$\eta > 45\%$. vs $\eta < 40\%$ for typical

Regenerative open Feedwater heater Rankine system
take steam from turbine to heat feed water



state 2,5 → 6 calculations

$$0 = m_2 h_2 + m_3 h_5 - m_1 h_1 \quad 0 = m_2 + m_3 - m_1$$

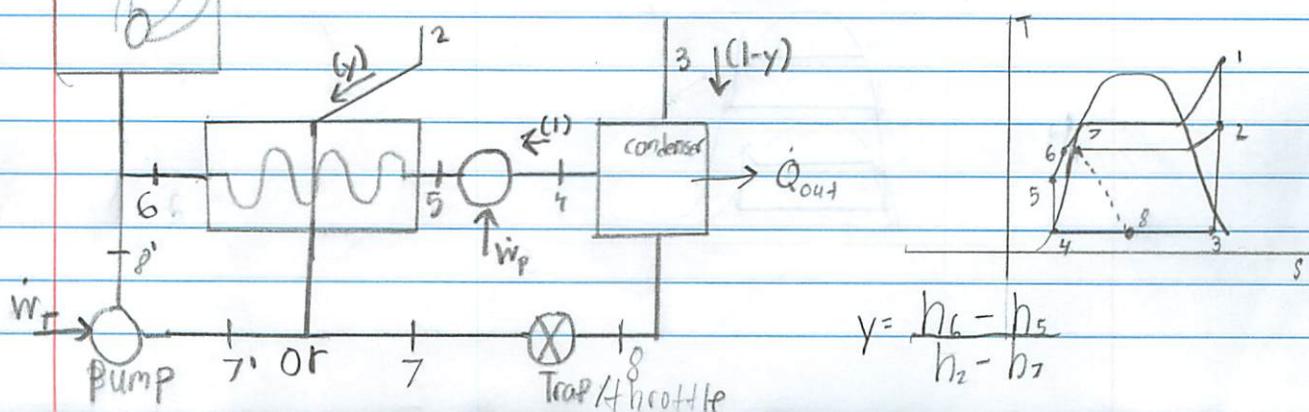
$$\text{rearrange to get: } y = \frac{h_6 - h_5}{h_2 - h_3}$$

$$\dot{W}_{HP} = m_1 (h_1 - h_2) \quad \dot{W}_{LP} = m_3 (h_2 - h_3)$$

$$\text{rearrange: } \dot{W}_t = h_1 - h_2 + (1-y)(h_2 - h_3)$$

$$\dot{W}_t = \frac{h_6 - h_7 + (1-y)(h_4 - h_5)}{m_1}$$

Closed Feedwater Heater: engineering assumption, 4 and 7 are $x=0$



Multiple feed water heaters

- more is better
- limiting factor is cost and space
 - also limited by calculations

calculating

- highest pressure - lowest feed water heater
- calculate all states first

Choosing your working fluid.

Inexpensive and abundant

non-toxic

chemically stable

noncorrosive

large enthalpy of vaporization

- give off lots of energy in turbine expansion

large Δv change during vaporization

- big Δv for turbine } relates to work

- small for pump

Water is all of these

Temp of heat source

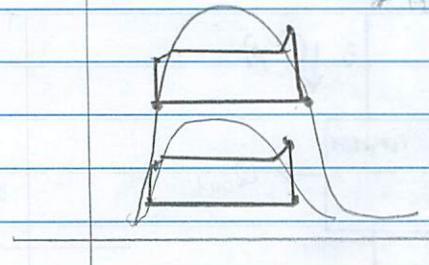
organic substances, organic ranking cycles

has C and H and possibly N

these have lower boiling points

Binary vapor cycle

The condenser of one gives enough heat to
be another cycles boiler



Cogeneration cycle: a power cycle with another useful output

- like using high-Temp steam for heating or whatnot
- Used at uconn

Back-pressure plant

take from condenser

Extraction plant

take of mass bleed fraction

$$\eta = \text{all useful energy} / Q_{\text{in}}$$

Chapter 9:

ideal gas working fluid

internal heat addition - working fluid chemically

Reacts to make heat

Brayton cycle : Jet engines

Otto cycle : cars

Diesel cycle : truck

Ideal gas equations:

$$\Delta h = \int c_p dT \quad \Delta U = \int c_v dT$$

$$\Delta S = \int c_v \frac{dT}{T} + R \ln \frac{V_2}{V_1} \quad \text{or} \quad \int c_p \frac{dT}{T} - R \ln \frac{P_2}{P_1}$$

Air Standard Model

Air is an ideal gas

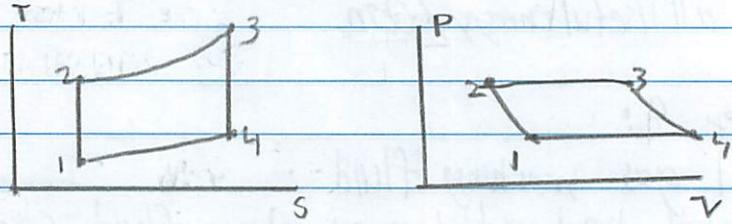
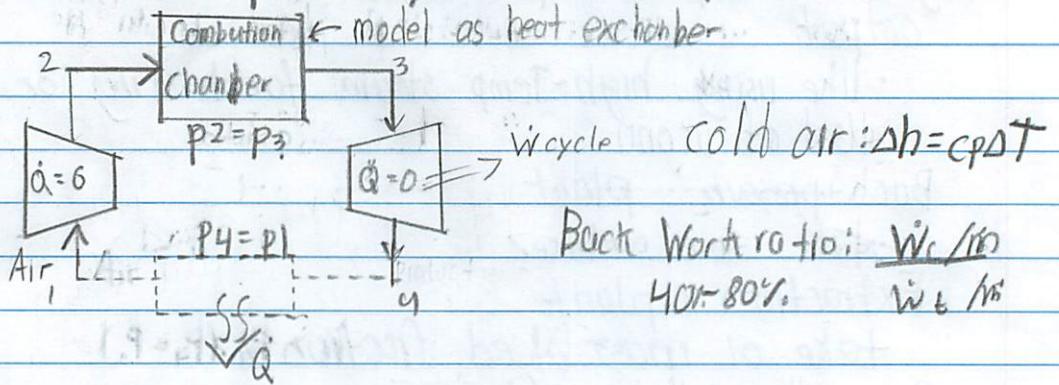
$$MW = 28.97 \text{ kg/mol}$$

Cold air: (300 K or 72°F)

constant specific heats

faster calc but less accurate

Gas turbine power cycle: Brayton cycle



$$\frac{T_4}{T_1} = \left(\frac{T_3}{T_2} \right)^{\frac{1}{k-1}}, \quad \eta = 1 - \left(\frac{1}{\left(\frac{P_2}{P_1} \right)^{\frac{1}{k-1}}} \right)$$

max T_3 is the temp that causes turbine to melt

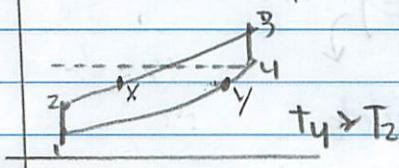
Higher pressure ratio means $\uparrow \eta$ but $\downarrow W_{net}$

Optimal pressure ratio:

$$\frac{P_1}{P_2} = \left(\frac{T_3}{T_1} \right)^{\frac{1}{2(k-1)}}$$

Regenerator:

State 4 flow preheats fluid before combustor

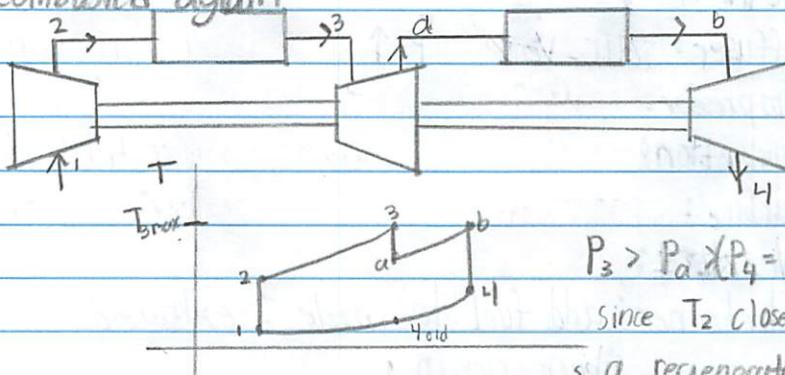


regenerator effectiveness:

$$\eta_{reg} = \frac{h_x - h_2}{h_4 - h_2} \quad \text{optimal } h_x = h_4$$

Reheat gas turbine:

We have an air-rich combustion, allows air to be combusted again



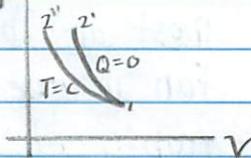
Compressor modification

$$\text{Intercooled gas: } \frac{\dot{W}_{1-2}}{m} = - \int_{P_1}^{P_2} v dp$$

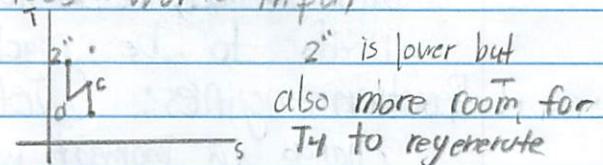
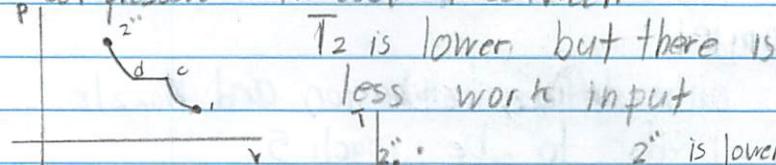
cool compressor to isothermal:

isothermal area behind the

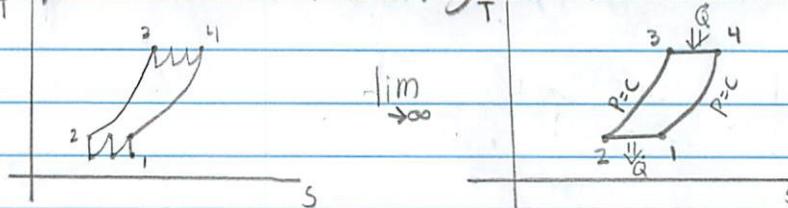
curve (work) is less input



Make two compressors with cooler in between:



Ericsson cycle: (infinite intercooling and reheat)



2-3 is regen
from T_4

$$\eta = 1 - \frac{T_c}{T_h}$$

Combining cycles:

Q_{out} becomes another cycles Q_{in}

Aircraft propulsion:

Brayton cycle has good thrust to weight

Turbojet:

Diffuser: air $V_e \downarrow$ $P \uparrow$

compressor:

Combustion:

Turbine:

Nozzle 1:

optional Afterburner: add fuel to nozzle 1 exhausted

burn again

$T \uparrow$ and $V \uparrow$

$$\text{Thrust} = m \Delta V_e$$

Turbofan:

most air bypasses combustion

Fan increases exist V

Turbo prop:

same as turbo fan

ramjet:

only diffuser, combustion, and nozzle

Needs to be mach 5

Reaction engines: (Jet/rocket engines)

change in momentum is from a reaction force

Nozzle: enthalpy to K.E.

Reciprocating engines: piston-cylinder assembly

spark ignition: air-fuel mix

Working fluid is sparked at end of compression
 <300 hp

compression ignition:

Working fluid is all air

at max compression-fuel is added and
burned from high temps

>300 hp

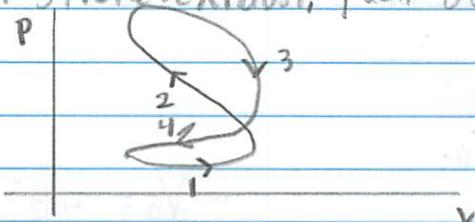
4 stroke cycle:

1st stroke: Fresh air/air-fuel drawn in \rightarrow TDC \rightarrow BDC

2nd stroke: compression $BDC \rightarrow TDC$

3rd stroke: power spark forces down piston

4th stroke: exhaust, push out spent mixture



Two strokes:

animatedengines.com

split engine in half so intake occurs below
piston and compression above

Reciprocating engine equations

$$\text{Volume ratio} : r = \frac{V_{BDC}}{V_{TDC}} = 1 + \frac{V_L}{V_c}$$

$$W_{cycle} = \oint pdV$$

Brake power output:

power at crankshaft:

$$4\text{-stroke} : W_{net} = n_c \frac{\dot{V}}{2} W_{cycle}$$

$$2\text{-stroke} : \dot{W} = n_c N_w$$

N_w : rev per second

n_c : number of cylinders

crankshaft torque:

$$T = \frac{\dot{W}}{2\pi N}$$

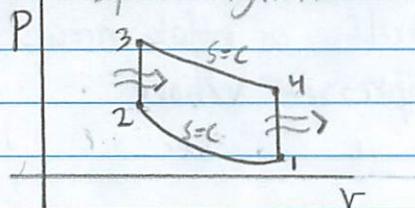
mean effective pressure

$$MEP = \frac{W_{cycle}}{V_d}$$

$$V_d = \frac{\pi}{4} B^2 \cdot S$$

displacement volume

Otto cycle: spark ignition



$$n = \frac{W_{cycle}}{Q_{in}}$$

$$\Delta U = Q - W$$

$$\underline{W_{1-2}} = \underline{U_1 - U_2} = \int pdv$$

$$\underline{W_{3-4}} = \underline{U_3 - U_4} = \int pdv$$

$$\underline{Q_{2-3}} = \underline{U_3 - U_2}$$

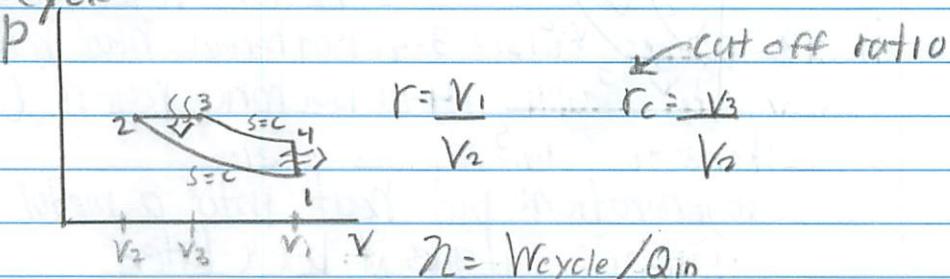
$$\underline{Q_{1-4}} = \underline{U_1 - U_4}$$

$$r = \frac{V_L}{V_2} = \frac{V_L}{V_2}$$

cold air otto: $\Delta U = C_v \Delta T$

$$r = \frac{V_1}{V_2} \quad \eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{1}{r^{k-1}}$$

Diesel cycle:



$$\frac{W_{1-2}}{m} = \frac{U_1 - U_2}{m}$$

$$\frac{W_{2-3}}{m} = P_2 (V_3 - V_2) \quad \frac{Q_{2-3}}{m} = U_3 - U_2 + \frac{W_{2-3}}{m}$$

$= h_3 - h_2 \leftarrow \text{only because constant } P$

$$\frac{W_{3-4}}{m} = U_3 - U_4 \quad \frac{Q_{4-1}}{m} = U_1 - U_4$$

Use ideal gas law:

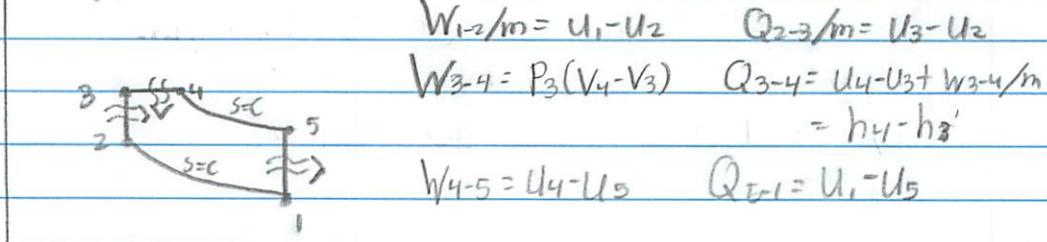
$$P_2 V_2 = R T_2, \quad P_3 V_3 = R T_3$$

$$T_3 = r_c T_2 \quad \text{because } P_2 = P_3$$

cold air diesel cycle:

$$\eta = \frac{1 - (U_4 - U_1)}{h_3 - h_2} = 1 - \frac{1}{r^{k-1}} \left(\frac{r_c^k - 1}{k(r_c - 1)} \right)$$

Duel cycle: otto-turbine duel:



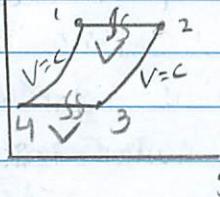
$$r = \frac{V_1}{V_2} \quad r_c = \frac{V_4}{V_3}$$

$$\eta = \frac{W_{\text{cycle, net}}}{Q_{\text{in, net}}}$$

ideal stirling cycle:

$$\eta = 1 - \frac{T_c}{T_h}$$

1-2



1-2: isothermal heat addition

2-3: isochoric regeneration (removal)

3-4: isothermal heat removal

4-1: isochoric regen (addition)

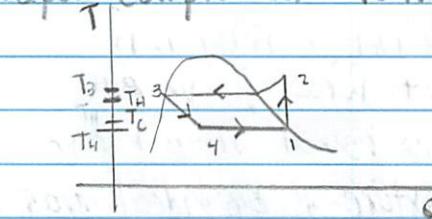
5

regeneration: put heat into a metal block
It gives it back latter

Refrigeration Cycles:

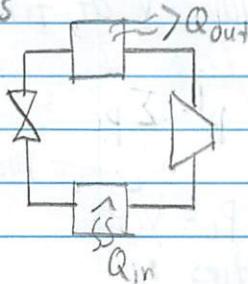
$$T_{C,C} \leq T_C \quad T_{C,H} \geq T_H$$

Vapor-compression refrigeration:



- 1-2: isentropic compression
- 2-3: isobaric heat rejection
- 3-4: isenthalpic expansion
- 4-1: isobaric heat addition

Components



condensator

1-2: compressor

2-3: Heat exchange to hot reservoir

3-4: Expansion Valve

4-1: Heat exchange to cold reservoir
≈ evaporator

$$1-2: \dot{W}_c = \dot{m}(h_1 - h_2) \quad 2-3: \dot{Q}_{out} = \dot{m}(h_3 - h_2), X_3 = 0$$

$$3-4: h_3 = h_4 \quad 4-1: X_1 = 1, \dot{Q}_{in} = \dot{m}(h_1 - h_4)$$

$$B = \dot{Q}_{in} / \text{ir cycle}$$

Refrigeration capacity:

rate of \dot{Q}_{in} (\dot{Q}_{in})

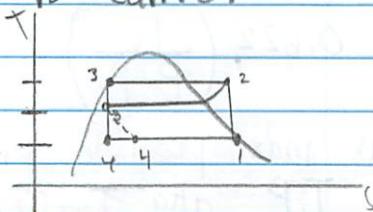
$$1 \text{ ton} = 200 \text{ BTU/min} = 3.5168 \text{ kW}$$

energy need to freeze 2000lb of water in one day

Cascade Refrigeration cycle: combined cycles

Heat pump: $\gamma = \dot{Q}_{out} / \text{ir cycle}$

VCR vs Carnot:



Mixtures of ideal gasses
mols or mass of each component

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

Dalton model:

say each component of the mixture is an ideal gas
and fills the entire volume V at temp T

Partial pressure

$$P_i = \frac{n_i RT}{V}$$

$$P = \sum P_i$$

$$P_i = y_i P \quad \text{← mol fraction}$$

other mixture properties

$$U = \sum U_i \quad H = \sum H_i \quad S = \sum S_i$$

general property:

$$B = \sum n_i b_i = \sum m_i b_i$$

$$b = \sum m_i b_i \quad \bar{b} = \sum y_i b_i$$

Moist air: dry air and water vapor

Psychrometry: study of moist air mixtures

Dry air is one ideal gas (a)

Water is the other (v)

$$m_v \ll m_a, \quad n_v \ll n_a$$

$$P_a = y_a P \quad P_v = y_v P \quad P = P_a + P_v \quad P_v \ll P_a$$

Humidity ratio:

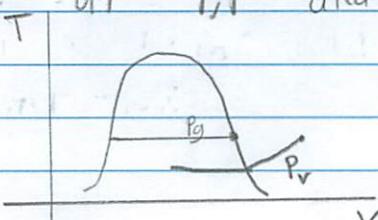
$$\omega = m_v / m_a$$

$$\text{using gas law, } \omega = 0.622 \left(\frac{P_v}{P - P_v} \right)$$

Relative humidity

$$\phi = \frac{P_v}{P_g}_{T,P}$$

P_g is max possible P_v
at T, P aka $P_{sat}(T)$



Moist air:

$$U = M_a u_a + m_v u_v, \quad U_L = M_a u_a + m_v u_v$$

M_a

$$u_v = u_g(T) \quad \text{because ideal only rely on temp}$$

Same with H and S

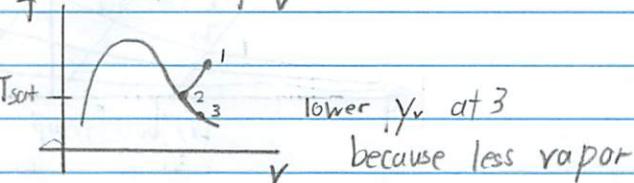
$$\text{except } s_v = s_g(T) - R \ln \phi$$

moist air and condensed water

$$P = P_a + P_v$$

start with moist air and cool at constant P
water $T - V$

T_{sat} is due
point temperature



$$\text{Humidity ratio } w = 0.622 \frac{P_v}{P - P_v}$$

produce saturated moist air: Adiabatically

$$\begin{array}{ccc} T_1 & \xrightarrow{\quad} & T_2 < T_1 \\ P_1 & \xrightarrow{\quad} & P_2 = P \\ w_1 & \xrightarrow{\quad} & w_2 = ? \\ \varphi_1 & \xrightarrow{\quad} & \varphi_2 = 100\% \\ & & \text{liquid water (w) @ } T_2 \end{array}$$

mass rate balance

$$\dot{m}_{a1} = \dot{m}_{a2}, \quad \dot{m}_{v1} + \dot{m}_{w1} = \dot{m}_{v2} + \dot{m}_{w2}$$

$$\frac{\dot{m}_{w2}}{\dot{m}_a} = w_2 - w_1$$

energy rate balance

$$0 = \dot{m}_{a1} h_{a1} + \dot{m}_{v1} h_{v1} + \dot{m}_w h_w - \dot{m}_{a2} h_{a2} - \dot{m}_{v2} h_{v2}$$

$$w_2 = 0.622 \frac{P_g(T_{2sat})}{P - P_g(T_{2sat})}$$

$$w_1 = h_{a2} - h_{a1} + w_2 (h_{v2} - h_w)$$

$$h_{v1} - h_w$$

Dry bulb temp

measure temp of moist air

$$T_{db} = T_1$$

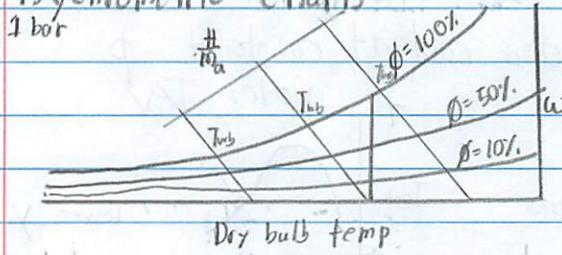
Wet bulb temp

put thermometer in wet wrapped wick

Flow air over and it evaporates air

$$T_{wb} = T_2 = T_{2sat}$$

Psychrometric Charts



Air conditioning:

Humidification:

adding water to moist air by evaporation or mixing

increases w

→ liquid water

with steam

Dehumidification:

opposite

reduce w

evaporative cooling

increase w

flow air over wet cloth

lose energy/temp as water is a coolant

AC equations:

adding water: $w_2 > w_1$

$$\dot{m}_{a1} = \dot{m}_o = \dot{m}_{a2}$$

$$\dot{m}_w = w_2 - w_1$$

$$\dot{m}_{v1} + \dot{m}_w = \dot{m}_{v2}$$

$$\dot{m}_o$$

$$\text{O} = \frac{\dot{Q}_{cv}}{\dot{m}_a} - \frac{W_{cv}}{\dot{m}_a} + h_{air}w_1h_{fr} + (w_2 - w_1)h_w - h_{az} - w_1h_{fr}$$

leaving water:

$$\dot{m}_{V1} = \dot{m}_w + \dot{m}_{V2}$$

$$\dot{m}_w = w_1 - w_2$$

$$\dot{m}_w$$

$$O = \frac{\dot{Q}_{cv}}{m_a} - \frac{\dot{W}_{cv}}{m_a} + \dot{h}_{a1} + w_1 h_{v1} - (w_1 - w_2) h_{w1} - \dot{h}_{a2} - w_2 h_{v2}$$

Constant composition:

$$\dot{m}_{V1} = \dot{m}_{V2}, \quad \dot{h}_{a1} = \dot{h}_{a2}$$

$$O = \frac{\dot{Q}_{cv}}{m_a} - \frac{\dot{W}_{cv}}{m_a} + (\dot{h}_{a1} - \dot{h}_{a2}) + w_1 (h_{v1} - h_{v2}) - w_2$$

Combustion:

exothermic reactions: Carbon, hydrogen, oxygen

complete combustion: all $C \rightarrow CO_2$, $H \rightarrow H_2O$, $S \rightarrow SO_2$

Combustion Air: 79% N_2 21% O_2

3.76 N_2 for 1 O_2

Hydrocarbon fuels

Natural gas: 1-4 carbons $CH_4/C_2H_6/C_3H_8/C_4H_{10}$

Gas: 5-9 carbons

Jet Fuel: 9-12 carbons

Diesel Fuel: 12-20 carbons

Methane example



$$C: 1 = b$$

$$H: 4 = 2c \quad C: 2 = b$$

$$O: 2a = 2b + c \quad a = 2$$

$$N: 2a \cdot 3.76 = 2d \quad d = 7.52$$

Air-fuel ratio

- can be by mass or by mol

Theoretical air

- Relative amount for complete combustion

Excess/Deficient air

ex: 25% excess air = 125% theoretical air

25% Deficient air = 75% theoretical air

Equivalence ratio:

$$\phi = \frac{AF_{\text{theoretical}}}{AF_{\text{actual}}}$$

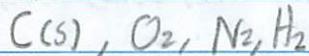
$$\text{or } \phi = \frac{FA_{\text{theoretical}}}{FA_{\text{actual}}}$$

Reference state - Non-reacting system

for ideal gas: $T = 298.15 \text{ K}$, $P = 1 \text{ atm}$

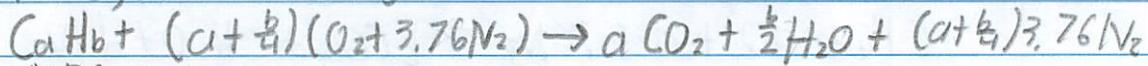
$$\bar{h}_f^{\circ} = 0$$

all other enthalpies are \pm this
at $\bar{h}_f^{\circ} = 0$



Other \bar{h}_f are tabulated

Open system reacting



NRG balance:

$$\dot{Q} = \dot{W}_{cv} + \dot{n}_{\text{fuel}} \bar{h}_{\text{fuel}} + \dot{n}_{O_2} \bar{h}_{O_2} + \dot{n}_{N_2} \bar{h}_{N_2} - \dot{n}_{CO_2} \bar{h}_{CO_2} - \dot{n}_{H_2O} \bar{h}_{H_2O} - \dot{n}_{N_2} \bar{h}_{N_2}$$

Divide through by \dot{n}_{fuel} and use ratios

$$\frac{1}{\dot{n}_{\text{fuel}}} (\dot{Q}_{cv} - \dot{W}_{cv}) = a \bar{h}_{CO_2} + \frac{b}{2} \bar{h}_{H_2O} + \left(a + \frac{b}{4}\right) 3.76 \bar{h}_{N_2}$$

$$\frac{1}{\dot{n}_{\text{fuel}}} (\dot{Q}_{cv} - \dot{W}_{cv}) = \bar{h}_r - \frac{1}{\dot{n}_{\text{products}}} \bar{h}_{\text{products}} - \frac{1}{\dot{n}_{\text{Reactants}}} \bar{h}_{\text{Reactants}}$$

Closed system

$$\bar{U}_p - \bar{U}_R = \frac{Q}{N_F} - \frac{W}{N_F}$$

For ideal gas: $\bar{U}(T) = \bar{h}(T) - \bar{R}T$

$$\approx \bar{h}_f^0 + \Delta \bar{h}$$
$$\approx \bar{h}(T) - \bar{h}(T_{ref})$$

Adiabatic flame temperature (T_{ad})

Constant pressure/enthalpy

Recall: $\frac{Q}{N_F} - \frac{W}{N_F} = \bar{h}_p - \bar{h}_R$

for this: $\bar{h}_p = \bar{h}_R$



Enthalpy of formation

From nat. state @ STP to where we are
Sensible enthalpy

Δh from refrence state due to ΔT

Equations of state

compressibility factor:

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

Virial coefficients

$$Z = 1 + \frac{B(T)}{V} + \frac{C(T)}{V^2} \dots$$

as $V \rightarrow \infty \therefore P \rightarrow 0$ and $Z \rightarrow 1$

Other terms account for interactions with multiple molecules

Van der Waals

$$P = \frac{RT}{V - b} - \frac{a}{V^2}$$

at T_c , $\frac{\partial P}{\partial V} = 0$ and $\frac{\partial^2 P}{\partial V^2} = 0$

use these to get a and b

Redlich-Kwong

$$P = \frac{RT}{V - b} - \frac{a}{V(V+b)T^{1/2}}$$

impressively accurate