Mead®

221

Applied Thermo

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ME 221 - Applied Thermodynamics
Course Structure - Fall 2010

Instructor: Professor Jim Drallmeier doesn't use blackboard
127 Toomey Hall
341-4710; drallmei@mst.edu
Office Hours: At any time by appointment (i.e. to ensure I am there)

Schedule: Lecture: 1:00 - 1:50 MWF

Prerequisite: Thermodynamics (ME 219, Grade of "C" or better)

Grading: 4 exams 20% each, 80% total

Approximate timing:

- Exam 1- week of 9/20
- Exam 2 - week of 10/18
- Exam 3 - week of 11/15
- Exam 4 - week of 12/13 (final exam week)

Homework 20% total

Final grades are curved. Approximate breakdown:

B-C cutoff at class mean score.
A: above 1 standard deviation from mean
D: below 1 standard deviation from mean
F: below 2 standard deviations from mean

I will provide you with your standing and current class statistics at any time in the semester upon request.

Exam dates are chosen by the class. Makeup exams will rarely be given. Vacations or lack of preparation are not valid reasons. If you are very ill, contact me **before** the exam so we can discuss options. If you contact me **after** the exam, you will receive a zero for that exam. If you require extra accommodations for exams, the exam must still be taken on the same day beginning at the scheduled class time. If you feel you have a justifiable conflict with the exam date chosen by the class (e.g. interview trip for a co-op), visit with me at least one week in advance to discuss options. No extra credit is available.

Homework:

- Homework will be assigned each class (typically 2 problems), due at the beginning of the next class.
- Typically, only one of the assigned problems will be collected.
- No late homework is accepted. However, the two lowest homework scores are dropped.
- Solutions to all problems will be posted, after homework is collected, outside of room ME 170. Solutions to my problems will be put on electronic reserve before exams (http://web.mst.edu/~lib-circ/). My solutions to book problems can only be posted in paper form.
- A problem session will be scheduled. Attendance is voluntary.
- Strategy for success: Review your solution with the posted solution immediately…not just before exam.

Class Notes:

- Given in class is an outline format.
- Essential to success on exams.
- Strategy for success: Review the problem examples provided in class before doing HW.

Text: Thermodynamics – Cengel and Boles, Sixth Edition

ME 221 Applied Thermodynamics
SCHEDULE

Text (C&B, 6th ed.)				Class Periods (approximate)
	I.		Review of Thermodynamics	
3.1 – 3.5		√ A.	Properties of a Pure Substance	[1]
3.6 – 3.7		√ B.	Ideal Gas Model	
Chapters 4&5		√ C.	First Law	[2]
Chapters 6&7		√ D.	Second Law	[1]
Chapter 8	II.		Exergy Analysis	
		√ A.	Introduction	[1]
		√ B.	Definitions	[1]
		√ C.	Efficiencies	
	9-10-10	D.	Examples	[1]
Chapter 9	III.		Gas Power Cycles	
1 - 3	9-10-10	A.	Intro	
4 - 5	9-13-10	B.	Otto Cycle	[1]
6		C.	Diesel Cycle	[1]
7		D.	Stirling Cycle	[1]
			EXAM 1	
8		E.	Brayton Cycle	[1]
9 - 10		F.	Brayton Cycle with Regeneration	[1]
11		G.	Jet Propulsion Cycle	[1]

Chapter 10	IV.	Vapor Power Cycles		
1, 2, 4	✓	A.	Rankine Cycle	[2]
5	✓	B.	Reheat Cycle	
6	✓	C.	Regeneration	[1]
	✓	D.	Examples	[1]
3	✓	E.	Losses	[1]
Chapter 11	V.	Refrigeration Cycles		
1-6	✓	A.	Vapor Compression Refrigeration Cycle	[2]
8	✓	B.	Air Standard Refrigeration Cycle	[1]
9	✓	C.	Absorption Refrigeration Cycle	[1]
	✓	**EXAM 2**		
	VI.	Gas Mixtures		
Chapter 13 (1-3)	✓	A.	Ideal Gas Mixtures	[3]
Chapter 14 (1-7)	Start 11-1-2010	B.	Gas Vapor Mixtures (Psychrometrics)	[5]
		EXAM 3		
Chapter 15	VII.	Chemical Reactions (Combustion)		
1	✓	A.	Fuels	[1]
2	✓	B.	Stoichiometry	[1]
3-5		C.	First Law for Reacting Systems	[4]
		EXAM 4		

MACAWEY.

HW: 97.2 (#32) (20%)

EXAMS: 68, 88, 99, X (80%)

(?) AVE: 87.4.

88.05 ↘

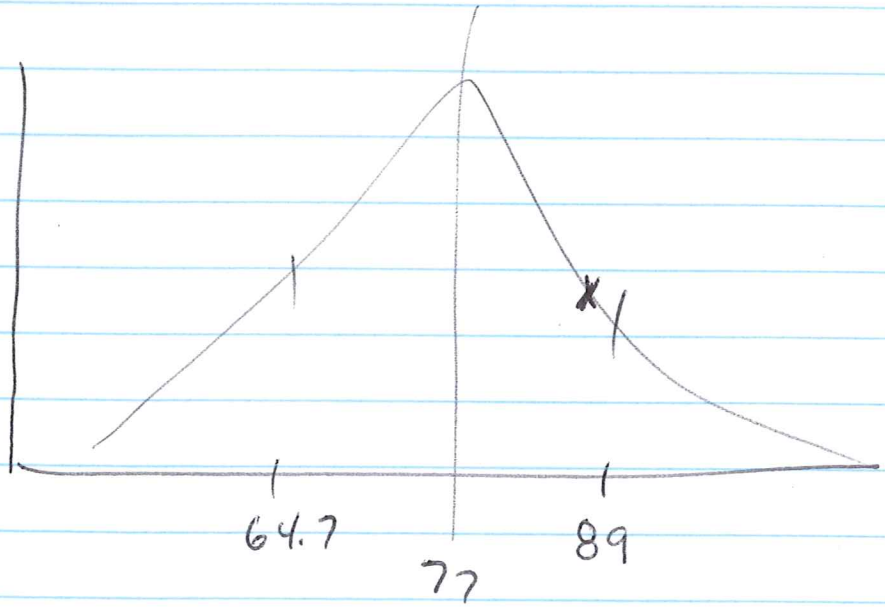
~~(.874)(.8) + (.2)(x) = (.89)~~

↓

For (A) need on EXAM IV: 92.8% ~~need on Exam IV: 95.4%~~ for A

CLASS: 77 MEAN.

17.2 STD. DEV.



ME 221 Applied Thermo

Notes 8-23

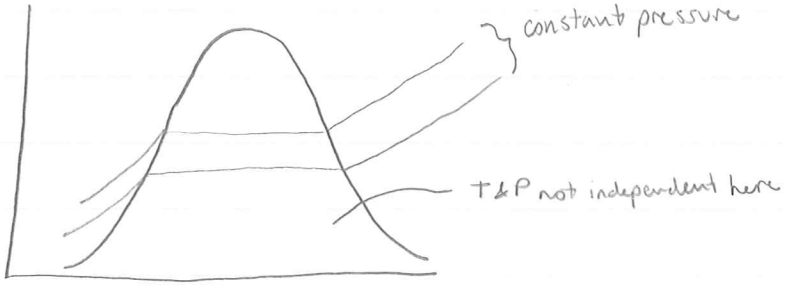
I. Review of thermo

A. properties of a pure substance

• pure sub: single species (eg. H_2O, CO_2, "Air")

1) state principle: for a pure substance, single phase, compressible substance: any 2 independent thermodynamic properties (P, T, u, h, s) establish the state.

Notes 8-25



- in the 2-phase region (under dome) quality: $= \frac{\text{mass vapor}}{\text{total mass}} = x$
- at saturated liquid line, quality $= 0$
- " vapor ", quality $= 1$

2) enthalpy: $h = u + Pv$ OR $H = U + PV$

3) specific heat: ammount of heat req'd per unit mass to raise T by 1 deg.

const. volume specific heat: $C_v = \frac{1}{m}\left(\frac{\delta Q}{T}\right)_v = \left(\frac{du}{dT}\right)_v$

const pressure specific heat, $C_p = \frac{1}{m}\left(\frac{\delta Q}{T}\right)_p = \left(\frac{dh}{dT}\right)_p$

Notes 8-25

B. Ideal Gas Model

1) provides an "eqn of state" $\boxed{PV = nR_uT}$

$\boxed{R_u = 8.314 \ \frac{kJ}{kmol\,K}}$ $PV = M_i R_i T$ R_i = gas constant for species 'i'

$R_i = \frac{R_u}{MW_i}$ ← molec. weight $Pv = R_iT$, $P = \rho R_i T$

2) limitations on application

- accurate at Low P & high T. air: accurate for most engineering apps

Water vapor: figure 3-49 in book

- correction to ideal gas law Z: compressibility factor $Z = \frac{Pv}{RT}$

if $Z = 1$, ⇒ ideal gas behavior. Z for many gases can be found by scaling T & P by critical values

Reduced $T = T_R = \frac{T}{T_{cr}}$

Reduced $P = P_R = \frac{P}{P_{cr}}$ } cr is "critical" values in book

Reduced $v = v_R = \frac{V}{R\frac{T_{cr}}{P_{cr}}}$ Fig. 3.51

3) ideal gas u & h calculations. For an ideal gas $h = h(T)$, $u = u(T)$

FUNCTIONS OF T ONLY ∴ $C_v \equiv \left(\frac{du}{dT}\right)_v = \frac{du}{dT}$

$du = C_v\,dT$ & $dh = C_p\,dT$

Note: $h_2 - h_1$ example, air $= h(T_2) - h(T_1)$ opt①

opt② or $h_2 - h_1 = C_p(T_2 - T_1)$ assuming C_p constant in T range

could find C_p (avg T)

opt③ $h_2 - h_1 = \int C_p(T)\,dT$ ← polynomial format

Also Note: $C_p - C_v = R$ $\frac{C_p}{C_v} = k$ k(air) ≅ 1.4

Notes 8-25

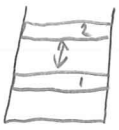
C. 1st law

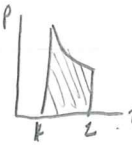
1) work $_1W_2 = \int_1^2 F\,dx$ depends on the path, not a state variable

sign convention: work done by system is positive (+)

" on system is negative (−)

• moving boundary work





$_1W_2$ = area under curve

HW due Monday 4.63, 4.29, 4.42

Notes 8-27-10

2) Heat transfer - energy transf. due to a finite ΔT

$_1Q_2 = \int_1^2 \delta Q$ dependent upon path

Sign convention: Heat INTO System (+)

Heat FROM System (−)

$_1Q_2 = 0$ ← Adiabatic

3) Fixed mass system (closed system)

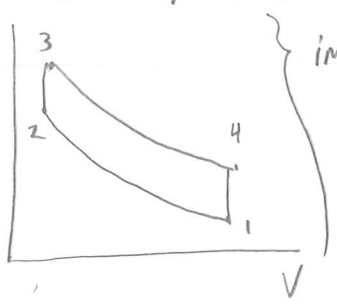
i) cons. of mass - $\therefore m$ = constant

ii) cons. of energy (1st law) $\underbrace{\delta Q - \delta W}_{\text{path dependent}} = \underbrace{dE}_{\text{state variable}}$

$$_1Q_2 - {}_1W_2 = E_2 - E_1 = \left(\tfrac{1}{2}mV^2 + mgz + U\right)_2 - (\quad)_1$$ fixed mass

iii) cycle - in a cycle, system returns to original state after passing through several processes

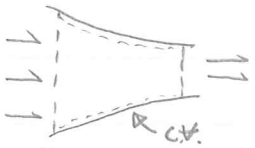
eg.



implies $E_2 = E_1$ $\therefore$ $W_{cycle} = Q_{cycle}$

4) control volume analysis (open system) Notes 8-27-10

- instead of fixed qty of mass, we select a region in space (C.V)



i) conservation of mass $\frac{d}{dt}\int_{C.V.} \rho\, dV = \Sigma \dot{m}_{in} - \Sigma \dot{m}_{out}$ ($\int_{C.V.}$: mass in the C.V.)

$$\boxed{\frac{dm_{cv}}{dt} = \Sigma \dot{m}_{in} - \Sigma \dot{m}_{out}}$$ steady state: in = out

ii) cons. of energy (1st law) $\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + (\dot{E}_{in} - \dot{E}_{out})$

consider each term

- $E_{cv} = \int_{cv} e\rho\, dV$ $\quad e = u + \frac{v^2}{2} + gz$
- $\dot{E} = \dot{m}e = \dot{m}\left(u + \frac{v^2}{2} + gz\right)$
- $\dot{W} = \dot{W}_{cv} + \dot{W}_f$ $\quad \dot{W}_{cv}$ = shaft work rate $\quad \dot{W}_f$ = flow work rate

flow work rate = $(P_{in} \cdot \text{Area}) \cdot (\text{flow vel.})_{in} - (P_o \cdot A)(\text{Flow vel.})_{out}$

ex: $\dot{W}_{F,IN} = (P \cdot A \cdot V)_{IN} = \dot{m} \cdot \left(\frac{P}{\rho}\right)$

showing that enthalpy is a product of flow work. ∴ use h in C.V. problems

— write 1st Law using above & $h = u + \frac{P}{\rho}$

FIND:
$$\boxed{\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W}_{cv} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right)}$$ control volume

5) examples

i) valve ⊗ assumption: STEADY, ADIABATIC, NO K.E. & P.E.

SOLN 1st law $\frac{dE_{cv}}{dt}^{0} = \dot{Q}^{0} + \dot{W}_{cv}^{0} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2}^{0} + gz^{0}\right) - \sum \dot{m}\left(h + \frac{V^2}{2}^{0} + gz^{0}\right)$

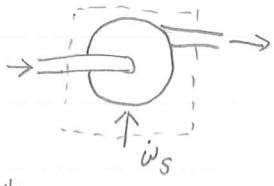
steady; adiabatic; no shaft

cons. of mass: $\dot{m}_{in} = \dot{m}_{out} \Rightarrow h_{in} = h_{out}$ (throttling)

Notes 8-30-10

HW #3 for WED 4.81, 5.51, 5.54 prob. session: wed 3-4pm 140

ii) Pump.



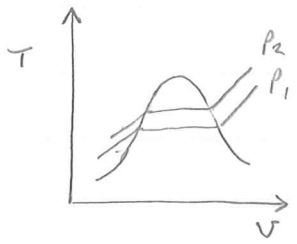
Assumptions: steady state, adiabatic, reversible, isentropic

1 inlet & 1 outlet

Soln $\frac{dE_{cv}}{dt}^{0} = \dot{Q}^{0} - \dot{W}_s + \Sigma \dot{m}_{in} h_{in} - \Sigma \dot{m}_{out} h_{out} \Rightarrow w = h_{in} - h_{out}$ (steady, isentrop)

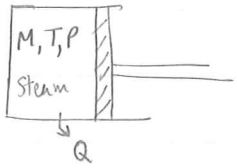
recall property relation $Tds = dh - vdP$ $ds = 0$ b/c isentropic

$\therefore$ $\boxed{w = \int_0^i v\,dP}$ NOTE • no work if $\Delta P = 0$ • Work is proportional to v



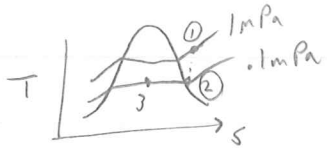
* $v_{vapor} >> v_{liquid}$ if v is constant (liquid) we can say $\boxed{v \int_0^i dP}$

iii) piston in cylinder



$M_1 = .5$ kg expansion to
$T_1 = 500$ C state 2
$P_1 = 1$ mPa $_1Q_2 = -50$ kJ

a) how much work extracted if expansion is allowed to go to 0.1 mPa w/o condensation



① given T, kP $v_1 = .354$ m³/kg $u_1 = 3124$ kJ/kg

② P = .1 MPa $x_2 = 1.0$ $T = 99.6°C$ $u_2 = 2506$ kJ/kg $v_2 = 1.694$

fixed mass 1st law $_1Q_2 - {}_1W_2 = V_2 - V_1$ $_1Q_2 - {}_1W_2 = m(u_2 - u_1)$

$\boxed{{}_1W_2 = 259 \text{ kJ}}$ (positive means OUT)

b) compression of steam under const. pressure until $v_3 = 1$ m³/kg $Q = ?$ $W = ?$

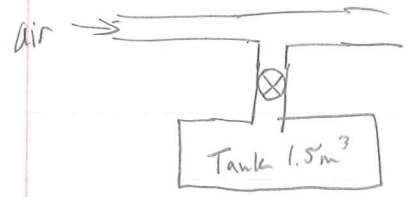
find quality x_3. $v_3 = v_{f_3} + x\, v_{fg\,3} \Rightarrow x = .59 \Rightarrow u_3 = 1650$ kJ/kg

${}_2W_3 = \int_2^3 P\,dV = P(V_3 - V_2) = P_m(v_3 - v_2) \Rightarrow {}_2W_3 = -34.7$ kJ/kg ("−" means Work OUT)

${}_2Q_3 = .5\text{kg}(1650 \text{ kJ/kg} - 2506 \text{ kJ/kg}) + (-34.7 \text{ kJ/kg})$

Notes 8-30-10

iv) Tank:



$P_{line} = 1MPa$ $P_i = 0$ Fill tank quickly ⇒ assume adiabatic

$T_{line} = 25°C$ $P_f = 1MPa$ find: mass in tank

Sol'n: need T_2 so we can find M_{tank}

1st law $\frac{dE_{cv}}{dt} = \cancel{\dot{Q}} - \cancel{\dot{W}_s} + \sum \dot{m}_{in}(h_{in}) - \cancel{\sum \dot{m}_{out}(h)_{out}}$

adiabatic, no shaft; nothing goes out

$E_{cv} = \int_{cv} e\rho dV = \int_{cv} u\rho dV$ now assume temp. across CV is constant

$E_{cv} = m_{cv}u$ $\frac{d(m_{cv}u)}{dt} = \dot{m}_{in}h_{in}$ $\int_i^f d(m_{cv}u) = \int_i^f \dot{m}_{in}h_{in}\,dt$

T_{in} is const. over time

$m_f u_f - \cancel{m_i u_i}^{0} = m_f u_f = h_{in}(m_f - m_i)$ $u_F = h_{in}$

Notes 9-1-10

HW # 4 for Fri 5.78, 5.124, 7.116 Prop session 3-4 room 140

for 7.116 $\dot{W}_p \rightarrow$ ② $P_2 = P_3$ ③ ↓ ○ → $\dot{W}_T$ ↓ ④ Want $\frac{\dot{W}_T}{\dot{W}_p}$

① $P_1 = P_4$

$P_1 = 1MPa$
$T_1 = 25°C$

continued from 8-30 $u_f = h_{in}$

$h_{in} = f(T_{only}) = 298.6 \frac{kJ}{kg \cdot K}$ $u_f = 298.6 \frac{kJ}{kg}$ K ⇒ $T_f = 417$ K

$m_f = \frac{P_f V_f}{R T_f} = 12.5\,kg$ Note: m_f would = 17.5 kg if $T_f = 25°C$

next page →

Notes 9-1-10

D. 2nd Law

1) INTRODUCTION

- 1st law relates exchange of energy flow
- 2nd law places restrictions on direction of flow

2) entropy in a system

- change in entropy for a system is given by $S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{REV}$

since entropy is a state function, the above applies regardless of if the process is reversible or irreversible

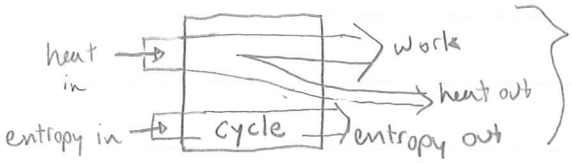
- Note if irreversible, $S_2 - S_1 = \int_1^2 \frac{dQ}{T} + {}_1S_{2\,gen}$

- reversible: a reversible process is one that once takes place can be reversed & results in no change in system or surroundings

NOTE: Entropy change is related to heat transfer (NOT work)

∴ entropy change in a system occurs with heat transfer not work

⇒ work can be completely converted into heat, but heat cannot... work



best would be reversible cycle

3) Interaction of systems & surroundings

for a process: $S_2 - S_1 = \int_1^2 \left(\frac{dQ}{T}\right) + {}_1S_{2\,gen}$ ∴ ΔS could be pos. or negative depending on sign on δQ

However, surroundings with which exchange is made also has a ΔS

$dS_{NET} = dS_{system} + dS_{surroundings} \geq 0$

Notes 9-1-10

4) Calculation of Entropy change

i) ideal gases For ideal gases $du = C_v dT$ $dh = C_p dT$ $Pv = RT$

RECALL $Tds = du + Pdv$ $\Rightarrow$ $\boxed{ds = C_v \frac{dT}{T} + R\frac{dv}{v}}$ with $h = u + Pv$

$\boxed{ds = C_p \frac{dT}{T} - R\frac{dP}{P}}$

$\boxed{S_2 - S_1 = \int_1^2 C_v \frac{dT}{T} + R\ln\frac{v_2}{v_1} \qquad S_2 - S_1 = \int_1^2 C_p \frac{dT}{T} - R\ln\frac{P_2}{P_1}}$

← use this (these) using constant C_p or C_v →

HW #5 due Wed: 7.93, 7.128, 8.22

Notes 9-3-10

a) for variable specific heats

$S_2 - S_1 = \int_1^2 C_p(t)\frac{dT}{T} - R\ln\frac{P_2}{P_1}$ $S_2^\circ(T_2) - S_1^\circ(T_1) = \int_1^2 C_p \frac{dT}{T}$

$\therefore$ $\boxed{S_2 - S_1 = \underset{f(T_2)}{S_2^\circ} - \underset{f(T_1)}{S_1^\circ} - R\ln\frac{P_2}{P_1}}$ IF PROCESS IS ISENTROPIC $\Rightarrow S_2 = S_1$

$\ln\left(\frac{P_2}{P_1}\right) = \frac{1}{R}\left(S_2^\circ(T_2) - S_1^\circ(T_1)\right)$

$\therefore$ IF we have $\frac{P_2}{P_1}$ & T_1, $\Rightarrow$ gives T_2

IF we have $\frac{v_2}{v_1}$, DEFINE v_r: $\ln v_r = \frac{1}{R}\int_{T_0}^{T} C_v \frac{dT}{T}$ $v_r = f(T)$ in table A17

$\therefore$ IF Isentropic ($S_2 = S_1$): $\left.\frac{v_2}{v_1}\right|_{S:\text{const}} = \frac{v_{R_2}(T_2)}{v_{R_1}(T_1)}$

$\therefore$ IF have volume ratio & T_1 $\Rightarrow$ gives T_2

Similarly $\left.\frac{P_2}{P_1}\right|_{S\text{const}} = \frac{P_{r2}}{P_{r1}}$

b) for const specific heats $S_2 - S_1 = C_{v,avg}\ln\left(\frac{T_2}{T_1}\right) + R\ln\left(\frac{v_2}{v_1}\right)$

$S_2 - S_1 = C_{p,avg}\ln\left(\frac{T_2}{T_1}\right) - R\ln\left(\frac{P_2}{P_1}\right)$

if Isentropic $C_v\ln\left(\frac{T_2}{T_1}\right) = R\ln\left(\frac{v_2}{v_1}\right)$ Note: $\frac{R}{C_v} = \frac{C_p - C_v}{C_v} = k - 1$

$\therefore$ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$ $\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k$ Pv^k constant

ISENTROPIC IDEAL GAS CONST. Spec. Heats

ii) 2nd law control mass analysis

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

iii) 2nd law for control volume

$$\boxed{\frac{dS_{cv}}{dt} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \sum \frac{\dot{Q}_{cv}}{T} + \dot{S}_{gen}}$$

5) isentropic efficiency - reference is the isentropic case

Work-producing: $\eta_{isen} = \frac{W_{actual}}{W_{isentropic}}$ Work-consuming: $\eta_{isen} = \frac{W_{isen}}{W_{actual}}$

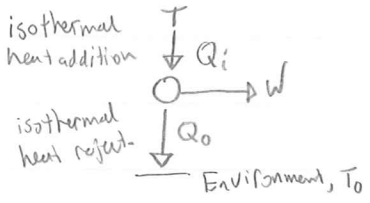
II Exergy Analysis - also termed "availability"

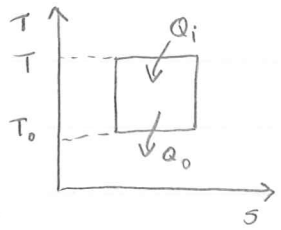
A) Introduction

- not all input energy can be converted to work
- what is the maximum work that can be done by a process?

→ that which is done reversibly and the final state in equil'm with the environment

Carnot Cycle





1st Law for a cycle:

$$\oint \delta Q = \oint \delta W$$

$$\Rightarrow W = Q_i - Q_0$$

2nd law $\Delta S = \int \frac{dQ}{T} + S_{gen}$ $\therefore \Delta S_i = \frac{Q_i}{T}$ $\Delta S_0 = \frac{Q_0}{T_0}$ (constant T & reversible)

Since $\Delta S = 0$ for a cycle, "s" is a state-function

$\therefore \frac{Q_i}{T} = \frac{Q_0}{T_0}$ $\boxed{W_{rev} = Q_{in}\left(1 - \frac{T_0}{T}\right)}$ maximum work possible

- only a fraction of the total Q_{in} can be converted to work

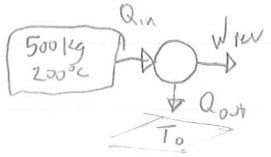
Ex: large furnace • supply heat 3MW ($\dot{m}h$) at 1100k, what is $\dot{W}_{rev}$ (max power)?

$\dot{W}_{rev} = \dot{Q}\left(1 - \frac{T_0}{T}\right) = 3MW\left(1 - \frac{273+25}{1100}\right) = 2.187$ ⇒ 27% is unavailable

HW #6 for Friday: 8.33 use avg. specific heats, + D1. Notes 9-8-16

Ex. 2: Max Work extracted from 500kg block of iron at 200°C, when $T_0 = 27°C$

sol'n



$\delta W = \delta Q_i \left(1 - \frac{T_0}{T}\right)$ but T of block changes

$W_{max} = \int_i^f \delta W = \int_i^f \left(1 - \frac{T_0}{T}\right) \delta Q_i$ use 1st law around block $\delta Q = dU$

$dQ = dU = mC\,dT = -\delta Q_i \Rightarrow W_{max} = -mC\left\{ \int_{T_i}^{T_0} dT - \int_{T_i}^{T_0} \frac{T_0}{T} dT \right\}$

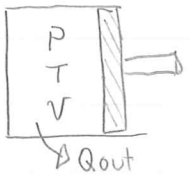
$W_{max} = -mC\left[(T_0 - T_i) - T_0 \ln\left(\frac{T_0}{T_i}\right)\right] = 8191$ kJ

Total energy of block $= mC(T_i - T_0) = 38{,}925$ kJ $\quad Q_{out} = 38{,}925 - 8191 = 30{,}734$

B) definitions

Exergy, X: max useful work that can be extracted from a system at a specified state

i) fixed mass system: what is max work (extractible) from following fixed mass @ spec'd state?



P_0, T_0, V_0

$\delta Q - \delta W = dU$

$-\delta Q_{out} - \delta W_{Exp} = dU$

$\delta W_{exp} = (P - P_0)\,dV + P_0\,dV$

useful work — Work on environment

We can also extract useful work from Q_{out} ie, W_{rev} @ carnot efficiency

$\delta W_{HT} = \delta W_{rev} = \left(1 - \frac{T_0}{T}\right)\delta Q_{out} \quad dW_{HT} = \delta Q_{out} - T_0\left(\frac{dQ_{out}}{T}\right)$

but 2nd law $dS = \frac{dQ}{T} \Rightarrow \frac{\delta Q_{out}}{T} = -dS \Rightarrow \delta W_{HT} = \delta Q_{out} + T_0\,dS$

$\delta Q_{out} = \delta W_{HT} - T_0\,dS$

Combine w/ 1st law $\rightarrow \ldots \underbrace{\delta W_{HT} + (P - P_0)\,dV}_{\text{useful work}} = -dU - P_0\,dV + T_0\,dS$

Notes 9-8-11

change in useful work that could be extracted = $-dU - P_0 dV + T_0 dS$

- now sum up (ie. integrate) as we take working fluid from current state to "dead state" (environmental)

$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0)$$

Per mass: $x = (u - u_0) + P_0(v - v_0) - T_0(s - s_0)$

Note: if we consider a process from state 1 to 2, we use the difference in X for maximum work $W_{max} = X_1 - X_2$ (or $W_{minimum\ in}$)

"Exergy balance" (fixed mass) 1st $Q - W = V_2 - V_1$

2nd $\int_1^2 \frac{dQ}{T} + S_{gen} = S_2 - S_1$

COMBINE! $Q - W - T_0 \int_1^2 \frac{dQ}{T} - T_0 S_{gen} = U_2 - U_1 - T_0(S_2 - S_1)$

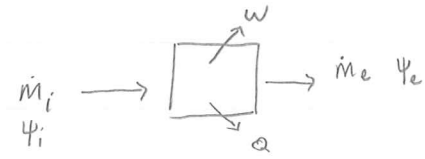
$$\int_1^2 dQ - T_0 \int_1^2 \frac{dQ}{T} - W - T_0 S_{gen} = U_2 - U_1 - T_0(S_2 - S_1)$$

$$\int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q - W - T_0 S_{gen} = X_2 - X_1 - P_0(V_2 - V_1)$$

$$\underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right) dQ}_{\text{max work from HT}} - \underbrace{\left[W - P_0(V_2 - V_1)\right]}_{\text{useful expansion work}} - \underbrace{T_0 S_{gen}}_{\text{destruction due to irreversibility}} = \underbrace{X_2 - X_1}_{\text{change in exergy}}$$

ii) control volume analysis

$$x = \psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2}$$



$W_{max} = \psi_1 - \psi_e$ (min)

Exergy bal: $\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} - T_0 \dot{S}_{gen} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i$

- $\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k$: work could extract from HT
- $\dot{W}$: shaft work
- $T_0 \dot{S}_{gen}$: irrev.
- $\sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i$: net max (or min) work

c) efficiencies

2nd law efficiencies

- Work-producing device: $\eta_{II} = \frac{W_{actual}}{\Delta X}$
- Work-consuming device $\eta_{II} = \frac{\Delta X}{W_{actual}}$

Notes 9-10-10

note → check how to find $s_2 - s_1$ with ideal gas. must use environment?

$\eta_{1st\ law}$ = what you get out / what you put in

III Gas power cycles

A. Intro

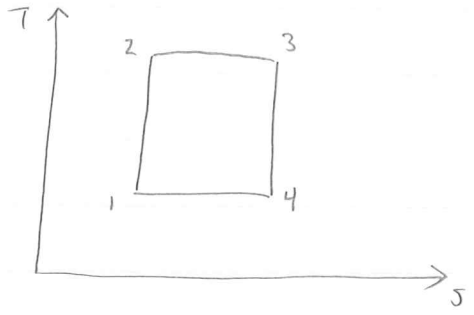
Carnot cycle

1→2 Isentropic compression

2→3 isothermal Heat Addition (Reversible)

3→4 Isentropic expansion

4→1 isothermal heat rejection (reversible)



1st law $\oint dw = \oint dQ$ $\quad w = {}_2Q_3 + {}_4Q_1$

2nd law $s_3 - s_2 = \int_2^3 \frac{\delta Q}{T} + \cancel{s_{gen}}^{0,\ rev.}$ $\quad {}_2Q_3 = T_2(s_3 - s_2) = "Q_{in}"$

${}_4Q_1 = T_4(s_1 - s_4) = "Q_{out}"$

$W_{net} = T_2(s_3 - s_2) - T_4(s_4 - s_1) = (s_3 - s_2)(T_2 - T_4) = "area\ in\ the\ box"$

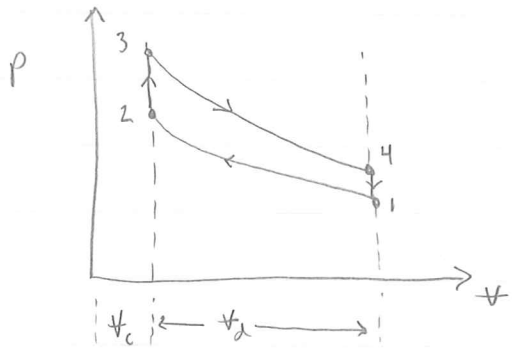
Notes 9-13-10

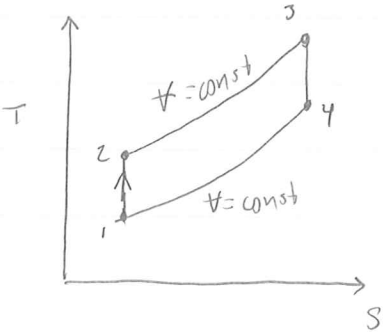
B. OTTO CYCLE : idealized version of spark-ignition engine

characteristic → fast combustion

i) otto cycle assumptions

- air is working fluid
- Ideal Gas, fixed mass cycle
- combustion process is modeled as a const $\forall$ heat addition process
- isentropic compression & expansion
- intake & exhaust process modeled as constant volume heat rejection





(1-2) isentropic compression

(2-3) const. volume heat addition

(3-4) isentropic expansion

(4-1) const. Volume heat rejection

ii) ANALYSIS (fixed mass)

1-2 • $\cancel{{}_1q_2}^{0} - {}_1W_2 = U_2 - U_1 \overset{C_{const}}{\Rightarrow} {}_1W_2 = C_V(T_1 - T_2)$

$\frac{T_2}{T_1} = \left(\frac{\forall_1}{\forall_2}\right)^{k-1}$

2-3 • ${}_2q_3 - \cancel{{}_2W_3}^{0} = U_3 - U_2 \overset{C_{const}}{\Rightarrow} {}_2q_3 = C_V(T_3 - T_2)$

3-4 • $\cancel{{}_3q_4}^{0} - {}_3W_4 = U_4 - U_3 \overset{C_{const}}{\Rightarrow} {}_3W_4 = C_V(T_3 - T_4)$

$\frac{T_3}{T_4} = \left(\frac{\forall_4}{\forall_3}\right)^{k-1}$

4-1 • ${}_4q_1 - \cancel{{}_4W_1}^{0} = U_1 - U_4 \overset{C_{const}}{\Rightarrow} {}_4q_1 = C_V(T_1 - T_4)$

$W_{Net} = {}_1W_2 + {}_3W_4 = {}_2q_3 + {}_4q_1$

IF assuming const. specific heats, $W_{net} = C_V(T_1 - T_2 + T_3 - T_4)$

$q_{in} = C_V(T_3 - T_2)$ $\quad \eta = \frac{W_{net}}{q_{in}} = \frac{T_1 - T_2 + T_3 - T_4}{T_3 - T_2} \Rightarrow \eta = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2}\right)$

Note: 1-2 & 3-4 are isentropic

Notes 9-13-10 continued

$$\therefore \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \quad \& \quad \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1}$$

$$V_1 = V_4 \;\&\; V_2 = V_3 \Rightarrow \frac{T_2}{T_1} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\eta_{th} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_4} - 1\right)} = 1 - \frac{T_1}{T_2}$$

$$\eta = 1 - \left(\frac{V_2}{V_1}\right)^{k-1}$$

Define: compression ratio, $r = \dfrac{\text{clearance volume + displacement volume}}{\text{clearance volume}}$

$$r = \frac{V_1}{V_2}$$

$$\Rightarrow \boxed{\eta_{th} = 1 - \frac{1}{r^{k-1}}}$$ OTTO CYCLE, const. specific heats

Definition: Mean Effective Pressure (MEP) $\boxed{MEP = \dfrac{\text{work}}{\text{displacem. volume}} = \dfrac{W_{net}}{V_1 - V_2}}$

Notes 9-15-10

iii) Example - Model SI engine w/ otto cycle

Given: $r = 8$ $Q_{in} = 7.5\ kJ$ $P_1 = 95\ kPa$ $T_1 = 17°C$ ("INDEX" conditions)

$V_1 = .0038\ m^3 = V_{cl} + V_d$

Find: a) P & T @ states 2, 3, 4 b) η_{th}, MEP

(1-2) isentropic compression IF const. specific heats, $P_2 = P_1\left(\frac{V_1}{V_2}\right)^k$ $T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1}$

$T_2 = 290k\,(8)^{0.4} = 666k$ $P_2 = 95\ kPa\,(8)^{1.4}$

IF Variable specific heats: $\frac{v_2}{v_1} = \left(\frac{v_{R,T_2}}{v_{R,T_1}}\right)$ $f(T_2)$, $f(T_1)$ ← these found in air tables using T_1

↑ known, $\frac{1}{r}$

Also $\cancel{s_2 - s_1}^{\,0} = s^\circ_{T_2} - s^\circ_{T_1} - R\ln\left(\frac{P_2}{P_1}\right)$

(2-3) const V heat addition ${}_2Q_3 - \cancel{W_3}^{\,0} = U_3 - U_2$

if Constant C: ${}_2Q_3 = m C_v (T_3 - T_2)$ $m = \frac{P_1 V_1}{R T_1} = \frac{(95\ kPa)(.0038\ m^3)}{(0.287)(290k)}$

$= 4.34 \times 10^{-3}$ $\Rightarrow T_3 = 3078k$ IF Variable C, ${}_2Q_3 = m(u_3 - u_2)$

↑ ↑ $f(T_3) - f(T_2)$

Now since V_{const}, m_{const}, $\frac{P_3}{P_2} = \frac{T_2}{T_2}$ $P_3 = 8069\ kPa$

Notes 9-15-10

(3-4) Isentropic expansion

IF const. $C_{p,v}$, $T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = 3078\left(\frac{1}{r}\right)^{0.4} = 1340k$

$\uparrow 1/r$

$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{k} = \ldots 439kPa$ IF Variable $C_{p,v}$, $\frac{V_3}{V_4} = \left(\frac{V_{r,T_3}}{V_{r,T_4}}\right)$

$\eta_{th} = \frac{W_{net}}{q_{in}} = \frac{{}_1W_2 + {}_3W_4}{{}_2q_3}$ IF variable $C_{p,v}$, ${}_1W_2 = u_1 - u_2$

${}_3W_4 = u_3 - u_4$

IF const. specific heats $\eta_{th} = 1 - \frac{1}{r^{k-1}}$

$MEP = \frac{W_{net}}{V_1 - V_2}$ $W_{net} = q_{in}\eta_{th} = 4.25kJ$ $V_2 = \frac{1}{r}V_1 = .000475m^3$

$MEP = 1275\ kPa$

iv) Non Isentropic compression & expansion

For Isentropic comp. & expansion $q = 0$

$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1}$; $T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1}$

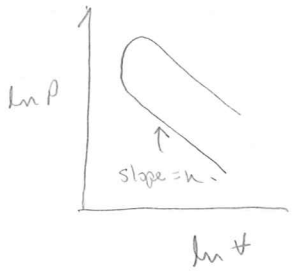
what if we assumed polytropic (Not adiabatic)

Compression: ${}_1q_2 - {}_1W_2 = u_2 - u_1$

expansion: ${}_3q_4 - {}_3W_4 = u_4 - u_3$

Also if polytropic $PV^n = const.$ $T_2 = T_1\left(\frac{V_1}{V_2}\right)^{n-1}$ $T_4 = T_3\left(\frac{V_3}{V_4}\right)^{n-1}$

Also $W = \int P\,dV$ & $PV^n = const.$ ${}_1W_2 = \frac{P_2V_2 - P_1V_1}{(1-n)}$ OR $\frac{R(T_2 - T_1)}{1-n}$



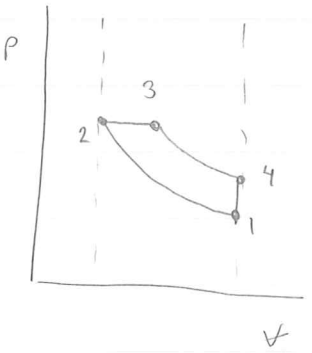
C. Diesel Cycle Actual Diesel process:

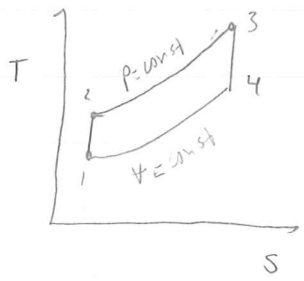
- Compression ignition (CI), Auto ignition
- Compress air only,
- Fuel is injected just before desired start of combustion
- non-homogeneous combustion ⇒ slow combustion

Notes 9-17-10

i) Cycle - assumptions

- air is the working fluid
- Fixed mass cycle
- combustion: constant P heat addition
- isentropic compression & expansion
- exhaust & intake: constant ∀ heat rejection





(1-2) Isentropic compression

(2-3) const p- heat addition

(3-4) Isentropic

(4-1) const ∀ heat rejection

ii) analysis (1-2) $\cancel{q_2}^{\,0} - {}_1w_2 = u_2 - u_1$ IF const $C_{v,p}$: ${}_1w_2 = C_v(T_1 - T_2)$

if const $C_{v,p}$: $\frac{T_2}{T_1} = \left(\frac{\forall_1}{\forall_2}\right)^{k-1}$, $\frac{P_2}{P_1} = \left(\frac{\forall_1}{\forall_2}\right)^{k}$

Variable $C_{p,v}$: $\frac{v_2}{v_1} = \frac{v_{R_2}}{v_{R_1}}\frac{T_2}{T_1}$ $\cancel{s_2 - s_1}^{\,0} = s^\circ_{T_2} - s^\circ_{T_1} - R\ln\left(\frac{P_2}{P_1}\right)$

(2-3) const p.: ${}_2q_3 - {}_2w_3 = u_3 - u_2$ But ${}_2w_3 = P_2(v_3 - v_2)$ ${}_2q_3 = (u_3 - u_2) + P_2(v_3 - v_2)$

$\Rightarrow {}_2q_3 = h_3 - h_2$ IF Const $C_{p,v}$, ${}_2q_3 = C_p(T_3 - T_2)$

(3-4) isentropic expansion, if const. $C_{p,v}$, $P_4 = P_3\left(\frac{\forall_3}{\forall_4}\right)^k$ (This is Not $\frac{1}{r}$)

But: $\frac{\forall_3}{\forall_4} = \frac{\forall_3}{\forall_2}\cdot\frac{\forall_2}{\forall_4}$ ⇒ $P_4 = P_3\left(\frac{T_3}{T_2}\cdot\frac{1}{r}\right)^k$

$\uparrow$ T_3/T_2

$T_4 = T_3\left(\frac{T_3}{T_2}\cdot\frac{1}{r}\right)^{k-1}$

(3-4) variable specific heat, isentropic

$$\left(\frac{v_4}{v_3}\right) = \frac{v_{r,T_4}}{v_{r,T_3}} \Rightarrow T_4$$

$r\left(\frac{T_2}{T_3}\right)$ ↑ $f(T_3)$ ↑

(4-1) constant volume heat rejection

$${}_4q_1 - {}_4w_1 = u_1 - u_4 \qquad {}_4q_1 = u_1 - u_4 \quad \text{IF const } C_{v,p} \quad {}_4q_1 = C_v(T_1 - T_4)$$

$$w_{net} = {}_1w_2 + {}_2w_3 + {}_3w_4 \qquad q_{net} = {}_2q_3 + {}_4q_1$$

$$w_{net} = q_{net} = (h_3 - h_2) + (u_1 - u_4)$$

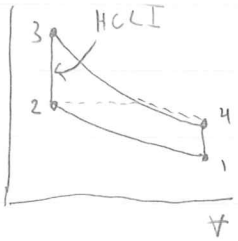
$$\boxed{\eta = \frac{w_{net}}{{}_2q_3}} = \frac{(h_3 - h_2) - (u_4 - u_1)}{h_3 - h_2} \leftarrow \text{this comes from: } \frac{{}_2q_3 + {}_4q_1}{{}_2q_3}$$

if we assume const. $C_{v,p}$ $\eta_{th} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{kT_2\left(\frac{T_3}{T_2} - 1\right)}$

Note: Drallmeier suggests just use $\frac{w_{net}}{{}_2q_3}$ to calculate

iii) comparison of Otto & diesel cycles look up HCCI

if r = fixed $\eta_{th,\,diesel} < \eta_{th,\,otto}$



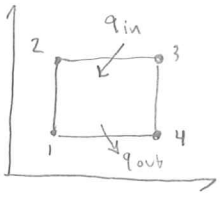
Exam covers up to Sterling cycle

Notes 9-20-10

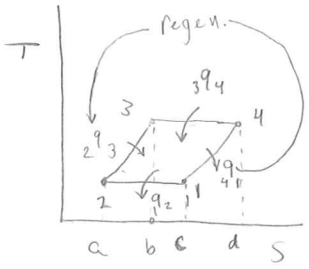
- focuses more on recent things (exergy, starts with D. problems)

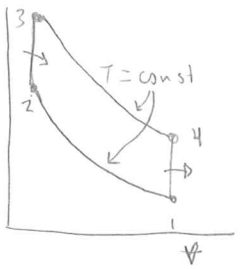
D. Stirling cycle

- recall carnot cycle
- isothermal compression & expansion



Note: a cycle which uses isothermal heat addtn & rejection should approach Carnot efficiency





(1-2) ISOTHERMAL COMPRESSION $_1q_2 - {}_1w_2 = \cancel{(u_2 - u_1)}^{\,0}$ $\quad {}_1q_2 = {}_1w_2 \quad {}_1w_2 = \int_1^2 P dv$

& $P = \frac{RT}{v}$ $\quad {}_1w_2 = RT \ln\left(\frac{v_2}{v_1}\right) = {}_1q_2$

also note: 2^{nd} Law $\Delta s = \int \frac{\delta q}{T} \Rightarrow {}_1q_2 = T\Delta s$

Define: Regenerator - captures heat rejected & stores energy for addition later in cycle

Note ${}_4q_{in}$ for (2-3), ie. area a 2 3 b a equals in magnitude "q out" for process (4-1) ie (c 1 4 d c) ∴ IF we use 100% effective regenerator to capture (4-1) & add back into cycle as ${}_2q_3$ then all heat addition is isothermal (3-4) and all heat rejection is isothermal (1-2)

⇒ cycle efficiency w/regenerator will equal carnot

Example

$T_1 = T_2 = 25°C$

$T_3 = T_4 = 1000°C$

$P_1 = 100 kPa$

$r = \frac{v_1}{v_2} = 10$

SOLN: (1-2) isothermal compression (reversible)

${}_1q_2 = {}_1w_2 = RT \ln\left(\frac{v_2}{v_1}\right)$

${}_1w_2 = .287 \frac{kJ}{kg \cdot K} \cdot 298 \ln\left(\frac{1}{10}\right) = -196.9 kJ/kg$

${}_1q_2 = -196.9 kJ/kg$

(2-3) const v heat addition: ${}_2q_3 - \cancel{{}_2w_3}^{\,0} = u_3 - u_2 = C_v(T_3 - T_2)$

${}_2q_3 = (0.7165 \frac{kJ}{kg \cdot K})(1273 - 298) = 698.6 kJ/kg$

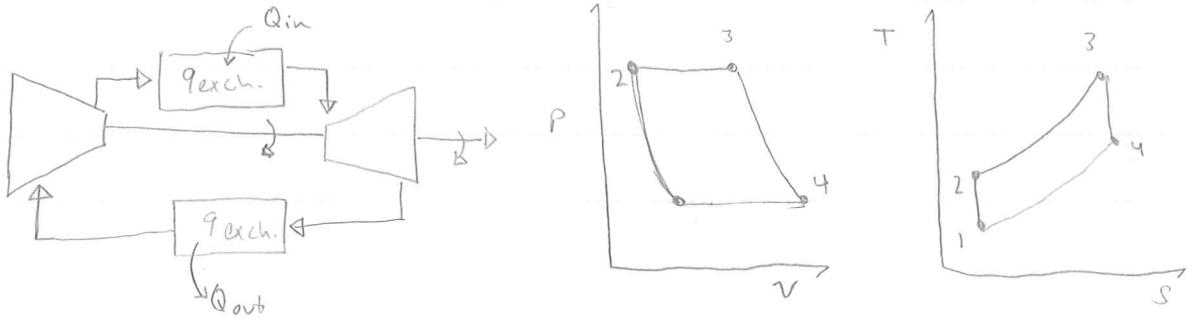
(3-4) isothermal expansion (rev) ${}_3q_4 = {}_3w_4 = RT_3 \ln\left(\frac{v_4}{v_3}\right)$

$= (0.287)(1273)\ln(10) = 841.3 \frac{kJ}{kg}$

(4-1) const v heat rejection ${}_4q_1 = C_v(T_1 - T_4) = -695.6 \frac{kJ}{kg}$

$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(-196.9 + 841.3)}{841.3} = 76.6\%$ efficiency

Brayton Cycle (closed)



(1-2) isentropic compression $\cancel{\dot{Q}}^{\,0}_{2} - \dot{W}_2 = \dot{m}(h_1 - h_2)$ $\quad \dot{W}_c = \dot{m}(h_1 - h_2)$

(2-3) P-const heat addition $\dot{Q}_3 - \cancel{\dot{W}}^{\,0}_{3} = \dot{m}(h_3 - h_2)$ $\quad \dot{Q}_{in} = \dot{m}(h_3 - h_2)$

(3-4) isentropic expansion $\dot{W}_T = \dot{m}(h_3 - h_4)$

(4-1) const. P heat addition $\dot{Q}_{out} = \dot{m}(h_1 - h_4)$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_T + \dot{W}_c}{{}_2\dot{Q}_3} = \frac{(h_3 - h_4) + (h_1 - h_2)}{(h_3 - h_2)}$$

if assume Const $C_{v,p}$ $\quad \eta_{th} = \dfrac{(T_3 - T_4) + (T_1 - T_2)}{T_3 - T_2} = 1 - \dfrac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \dfrac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$

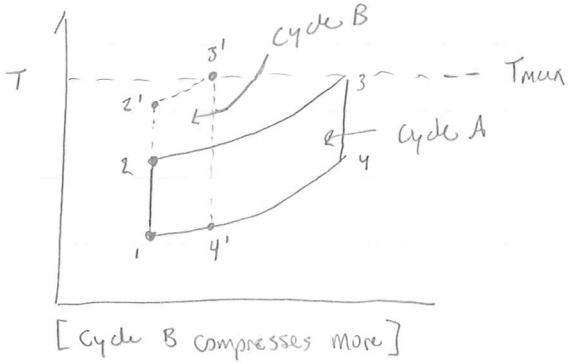
Using isentropic relations $\quad \dfrac{P_2}{P_1} = \left(\dfrac{T_3}{T}\right)^{\frac{k}{k-1}}$ $\quad \dfrac{P_3}{P_4} = \left(\dfrac{T_3}{T_4}\right)^{k/k-1}$ $\quad P_2 = P_3$; $P_4 = P_1$

$$\Rightarrow \frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \therefore \quad \eta_{th} = 1 - \frac{T_1}{T_2}$$

$$\boxed{\eta_{th} = 1 - \frac{1}{(P_2/P_1)^{k-1/k}}}$$

- Brayton cycle
- const. spec heats

- $\dfrac{P_2}{P_1}$ = compressor "pressure ratio"
- as $\dfrac{P_2}{P_1} \uparrow$, $\Rightarrow \eta_{th} \uparrow$



[Cycle B compresses more]

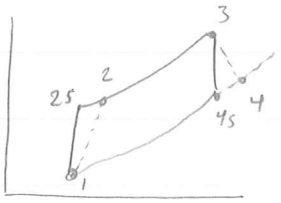
$\eta_{th}|_B > \eta_{th}|_A$

$W_{net}|_A > W_{net}|_B$

$\Rightarrow$ if I want the same power out,

$\dot{m}|_B > \dot{m}|_A \Rightarrow$ Cycle B will be a bigger system

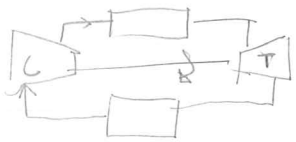
Losses:



$$\eta_{comp} = \frac{w_{cs}}{w_c}$$

$$\eta_{turb} = \frac{w_T}{w_{Ts}}$$

Example



$\frac{P_2}{P_1} = 6$ $T_1 = 300K$ $T_3 = 1100K$

Find: w_c, w_T, η_{th}

Soln (1-2) isent. comp: $\dot{w}_c = \dot{m}(h_2 - h_1)$ $w_c = c_p(T_2 - T_1)$

$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{k-1/k} = 300(6)^{.4/1.4} = 501K$! ~~$s_2 - s_1$~~ $= s^\circ_{T_2} - s^\circ_{T_1} - R\ln\left|\frac{P_2}{P_3}\right)$

$w_c = 1.005(300 - 501) = -201$

(2-3) const P: q_{in} $_2q_3 = h_3 - h_2 = c_p(T_3 - T_2) = 1.005(1100 - 501)$

$_2q_3 = 599 kJ/kg$

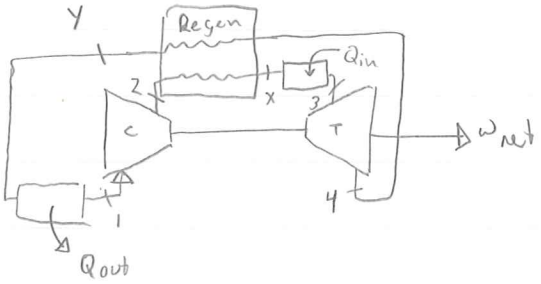
$\eta_{th} = \frac{w_{net}}{q_{in}} = $ const $c_{p,v}$: $= 1 - \left(P_2/P_1\right)^{\frac{k-1}{k}} = 1 - \frac{1}{(6)^{0.4/1.4}} = 0.40$

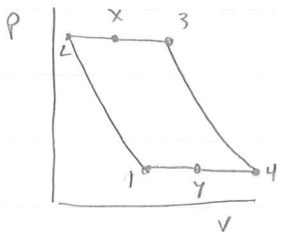
$w_{net} = 0.40(599) = 240$ kJ/kg $\Rightarrow w_T = w_{net} - w_c = 240 + 201 = 441$ kJ/kg

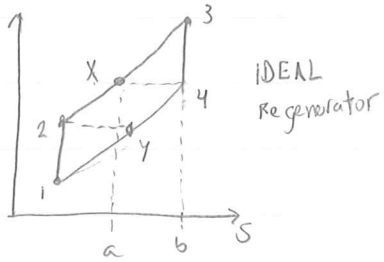
OR, $w_T = c_p(T_3 - T_4)$

F) Regeneration

Goal: utilize energy that remains in the flow after the turbine to preheat flow into the combustor







Note; if Regen is perfect, $T_4 = T_x$ & $T_2 = T_y$

- $T_4 > T_2 \Rightarrow$ so we can effectively preheat
- $Q_{in} =$ a-x-4-b
- regenerator efficiency: $\eta_{regen} = \dfrac{h_x - h_2}{h_4 - h_2}$

Analysis $w_{net} = w_T + w_2 = (h_3 - h_2) + (h_1 - h_2)$

const $c_{p,v} \Rightarrow c_p[(T_3 - T_2) + (T_1 - T_2)]$

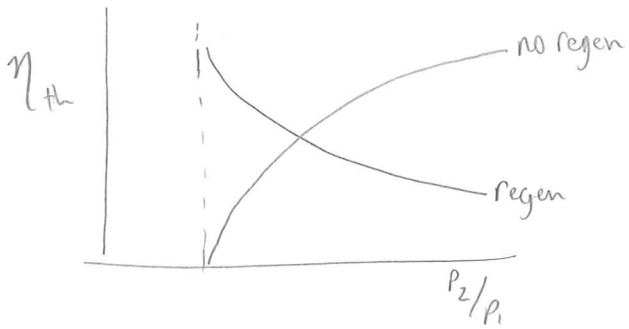
$q_{in} = h_3 - h_x = c_p(T_3 - T_x)$

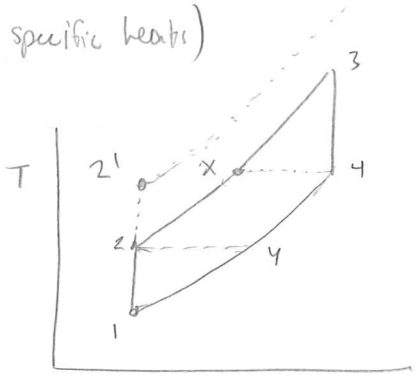
IDEAL REGEN, $T_x < T_4 \Rightarrow q_{in} = w_T$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_T + w_c}{w_T} = 1 + \frac{w_c}{w_T} = 1 + \frac{(T_1 - T_2)}{(T_3 - T_4)} = 1 - \frac{(T_2 - T_1)}{(T_3 - T_4)}$$

$$= 1 - \frac{T_1\left(T_2/T_1 - 1\right)}{T_3\left(1 - T_4/T_3\right)} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{k-1/k} \Rightarrow \frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)$$

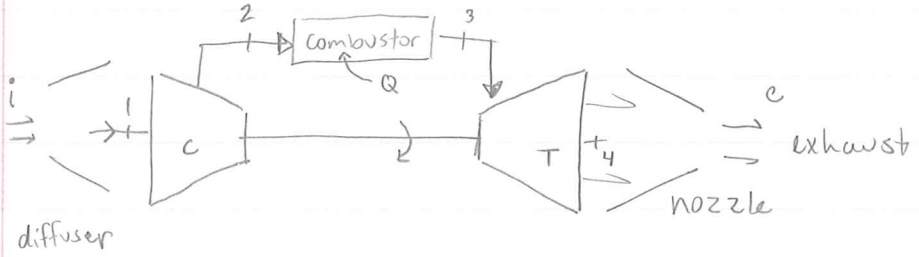
$$\eta_{th} = 1 - \frac{T_1}{T_3}\left(\frac{P_2}{P_1}\right)^{k-1/k} \quad \text{(const specific heats)}$$



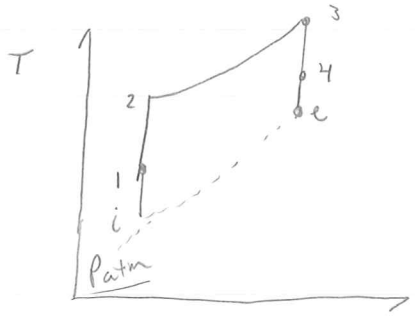


Notes 9-24-10

G) jet propulsion cycle



Propulsion from momentum flux, or "thrust" from the high velocity gases leaving turbine



Open V. of Brayton cycle

look for pictures of Florida air force combat museum

Notes 9-27

on calendar ✓ Due Friday: D14, 15

✓ Exam Wed: air tables given out, D. Problems are previous exam Q's

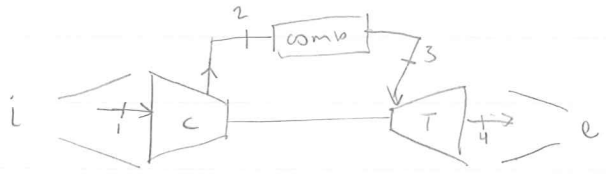
Know how to draw T-s & P-v cycles for every cycle

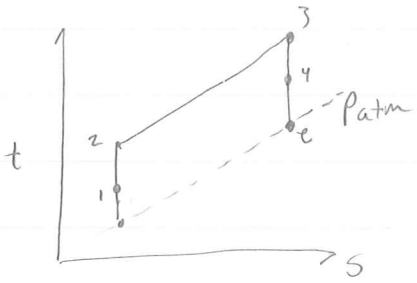
4 problems, (will not ask for all parts a-d as in D. problems

otto, diesel, sterling, brayton?

go over Diesel cycle ii) 3-4 $\frac{V}{V}$ terms

Example





IDEAL TURBOJET

$P_i = 26.5$ kPa, $T_i = 223$ k } at 10km

$V_i = 265$ m/s

$\dot{m}_{air} = 30$ kg/s

Comp ratio $\frac{P_2}{P_1} = 4.5$

$\dot{Q} = 30{,}000$ kJ/s

Find thrust: $= \dot{m}(V_e - V_i)$

Diffuser: isentropic $q - w = \left(h_1 + \frac{V_1^2}{2}\right) - \left(h_i + \frac{V_i^2}{2}\right)$

0, ie small compared to inlet

$h_i + \frac{V_i^2}{2} = h_1$ $\quad T_1 = T_i + \frac{V_i^2}{2C_p} = 223\,k + \frac{1}{2}(265\ m/s)^2\left(\frac{1}{1005\ J/kg\cdot k}\right)\left(\frac{1\ J}{kg\ m^2/s^2}\right)$ ✖ watch units here

$T_1 = 258$ k $\quad P_1 = P_i\left(\frac{T_1}{T_2}\right)^{k/k-1}$ $\quad \left[s_1 - s_i = s^\circ_{T_1} - s^\circ_{T_i} - R\ln\left(\frac{P_1}{P_i}\right)\right]$

$P_1 = 44.2$ kPa Compressor, isentropic $P_2 = 4.5\,P_1 = 198.9$ kPa

$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 258\,(4.5)^{0.4/1.4} = 396.7$ k $\quad q - w_c = h_2 - h_1$

$w_c = C_p(T_1 - T_2) = -139$ kJ/kg Const P combustor: $q - w = h_3 - h_2$ ($w = 0$)

$q = C_p(T_3 - T_2)$ $\quad \dot{Q} = \dot{m}\,C_p(T_3 - T_2)$ $\quad T_3 = 1397$ k

Turbine (isentropic) $q - w = h_4 - h_3$ $\quad w_T = C_p(T_3 - T_4)$ $\quad w_T$ MUST EQUAL $-w_c$

139 kJ/kg $\quad T_4 = T_3 - \frac{w_T}{C_p}$ $\quad T_4 = 1258$ k

$P_4 = P_3\left(\frac{T_4}{T_3}\right) = 198.9\ kPa\left(\frac{1258}{1397}\right)^{1.4/.4}$ $\quad \boxed{P_4 = 137.8\ kPa}$

Nozzle (isentropic) $T_e = T_4\left(\frac{P_e}{P_4}\right)^{k-1/k}$ $\quad P_e = P_i$ $\quad T_e = 785$ k

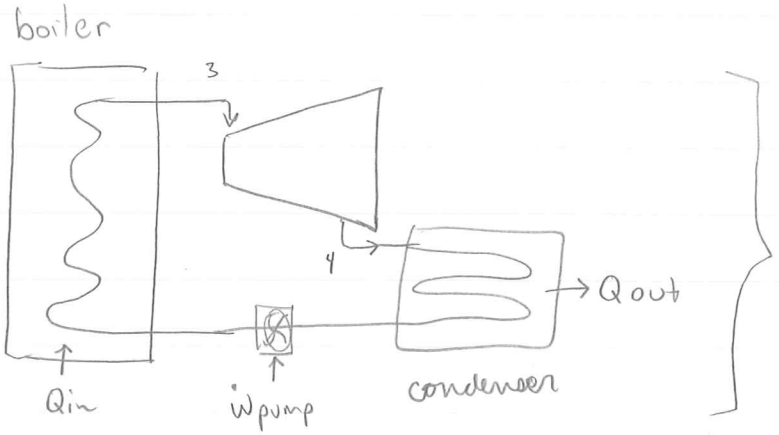
$q - w = \left(h_e + \frac{V_e^2}{2}\right) - h_4$ $\quad \frac{V_e^2}{2} = C_p(T_4 - T_e)$ $\quad V_e = 973$ m/s

Thrust $= \dot{m}(V_e - V_i) = 30\ kg/s\ (973 - 265\ m/s) = 2.12(10^4)$ N $\sim$ 4766 lb thrust

Notes 10-1-10

IV Vapor Power Cycle

A: Rankine Cycle - working fluid is a liquid-vapor mixture, typically water



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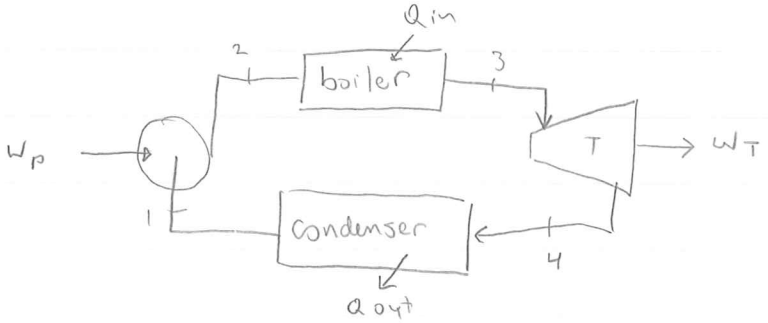
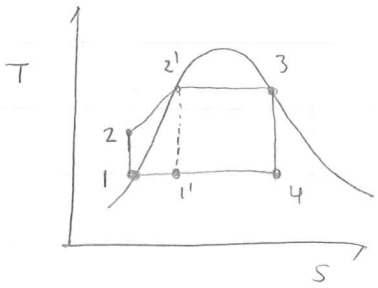




(1-2) isentropic pump

(2-3) const p. Qin

(3-4) isentropic expansion

(4-1) const. p. heat reject

2) analysis next pg.

* note: if we replace 1 with 1', we have the carnot cycle. However, pumping a liq/vap mixture is not practical

Notes 9-10-10

2) analysis, Ideal Rankine Cycle Boiler 3MPa $X_3 = 1.0$

condenser $P = .1 MPa$ $X_1 = 0$

Soln $P_2 = P_3 = 3MPa$ $X_3 = 1.0 \Rightarrow T_3 = 233.9^{\circ}C$ $h_3 = 2804.1 \frac{kJ}{kg}$

$S_3 = 6.1869 \frac{kJ}{kg}$ $P_4 = P_1 = 0.1MPa$ $X_1 = 0 \Rightarrow T_1 = 99.62^{\circ}C$

$h_1 = 417.44 \frac{kJ}{kg}$ $S_1 = 1.3025 \frac{kJ}{kg}$ $v_1 = 0.001043 \frac{m^3}{kg}$

3-4) isentropic expansion ~~q_4~~ $^{\circ} - {}_3w_4 = {}_3h_4$ $w_T = h_3 - h_4$

$S_3 = S_4 = 6.1869 \frac{kJ}{kg}$ $P_4 = 0.1 MPa \Rightarrow S_4 = 6.1869 = S_f + X_4(S_{fg})$

$\ldots X = 0.8064$ $h_4 = h_f + X_4 h_{fg} \ldots h_4 = 2238$

$W_T = 2804.1 - 2238 = 566 \frac{kJ}{kg}$

(4-1) condenser $q - w^{\circ} = h_1 - h_4$ $q = h_1 - h_4 = -1820 \frac{kJ}{kg}$

(1-2) pump ~~q~~ $^{\circ} - w = h_2 - h_1$ $w = h_1 - h_2$

have: $S_1 = S_2$ $P_2 = P_3$ define state 2 w S_2 & P_2

~~(comp. liquid tables)~~ recall: $w = -\int v dP$ & $v_1 \simeq v_2$

$w_p = v_1(P_1 - P_2) = .001043 (100kPa - 3000kPa)$ $w_p = -3.025 \frac{kJ}{kg}$

(2-3) BOILER ${}_2q_3 - {}_2w_3^{\circ} = h_3 - h_2$ ${}_2q_3 = h_3 - h_2$

Find h_2: $w_p = h_1 - h_2$ $h_2 = h_1 - w_p = \ldots$ 420.5 $\frac{kJ}{kg}$

${}_2q_3 = 2384 \frac{kJ}{kg}$

$$\eta_{th} = \frac{w_{net}}{{}_2q_3} = \frac{W_T + W_p}{{}_2q_3} = \frac{566 - 3.025}{2384} = 0.236$$

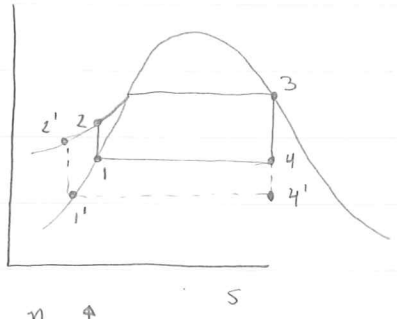
23.6 %

Notes 10-4-10

Exam 1 high 99
Statistics low 31
mean 75.2
st dev. 16.7

3) cycle T & P variations

i) condenser P



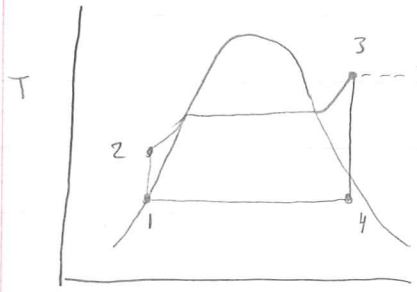
Recall for a Carnot cycle

$\eta_{th} = 1 - \frac{T_L}{T_H}$ ∴ as T_H & T_L become further apart, η_{th} ↑

advantage: T_L is reduced ∴ η_{th} ↑

disadvantage: $x_{4'} < x_4$ at turbine outlet. lower quality will results in turbine damage

ii) Superheat



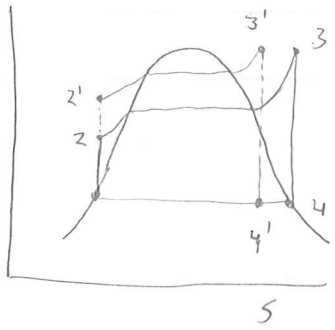
adv. increased quality of turbine
increased η_{th}

disadv.: amount of superheat limited by material constraints into turbine

iii) boiler pressure

adv: $T_{h,avg.}$ ↑, ⇒ η_{th} ↑

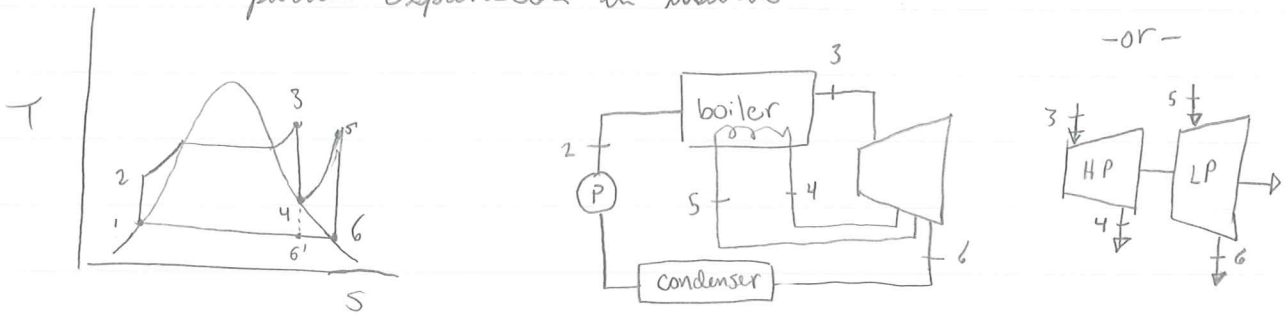
disadv: lowers quality out of turbine



Notes 10-4-10

B. reheat goal: increase quality leaving turbine

approach: reheating working fluid in boiler after partial expansion in turbine



Notes: • η_{th} is roughly the same.

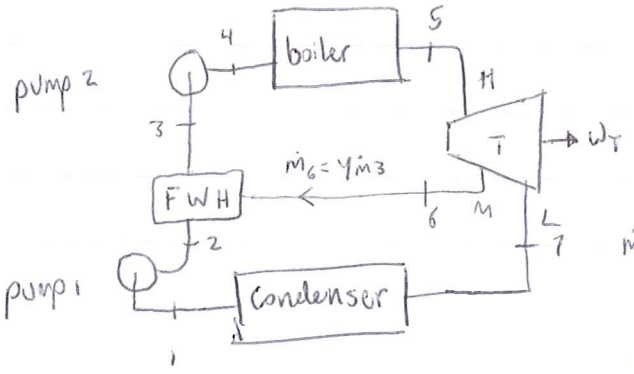
• $x_6 > x_{6'}$ (main advantage)

• $q_{in} = {}_2q_3 + {}_4q_5$ $\qquad w_T = {}_3w_4 + {}_5w_6$

Notes 10-6-10

C. Regeneration goal: raise temperature T_H where heat is added to (boiler)

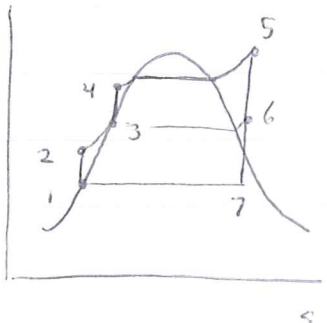
approach: use small amount of steam from turbine to "preheat" fluid while it is being pumped ("feed water") (in liquid phase)



$\dot{m} = (1-y)\dot{m}_3$

$\dot{m}_3 = \dot{m}_4 = \dot{m}_5$

Open feedwater heater continued



Notes: • $q_{in} = {}_4q_5$

• $\dot{m}$ is NOT CONST Through the system

• state 3 is typically taken to be saturated

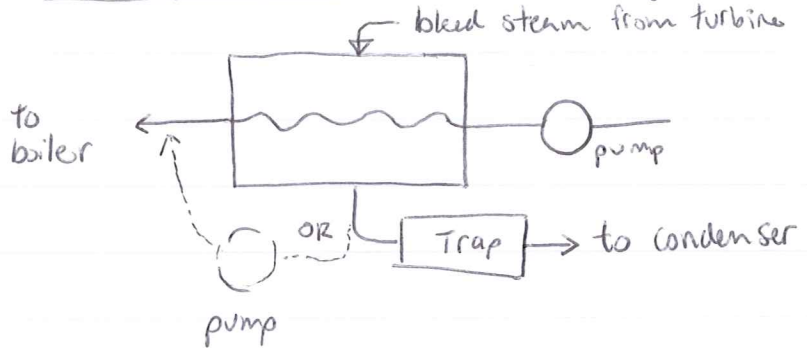
• open FWH mixes bleed steam & feedwater

⇒ good heat transfer

⇒ $P_2 = P_3 = P_6$

$P_2 = P_3 = P_6$

Closed feedwater heater • keeps fluid separated



Note: feedwater pressure & bleed steam pressure do not need to be the same

Analysis Open FWH • $P_6 = P_2 = P_3$ • FWH adiabatic

Find: fraction of • $x_3 = 0$

steam bled from turbine, y

To Find y, do analysis of FWH, NOT Turbine!

C.V. around FWH:

1st law $\cancel{\dot{Q}}^{0} - \cancel{\dot{W}}^{0} = \Sigma \dot{m} h_o - \Sigma \dot{m} h_i \Rightarrow \dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3$

$\frac{\dot{m}_2}{\dot{m}_3} + \underbrace{\frac{\dot{m}_6}{\dot{m}_3}}_{y} = 1$ $\quad \frac{\dot{m}_2}{\dot{m}_3} = 1-y$ $\quad (1-y)h_2 + y h_6 = h_3$

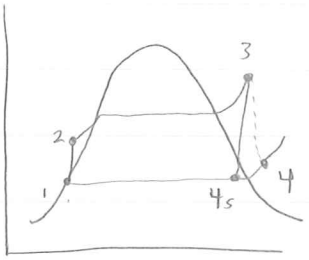
$y = \frac{h_3 - h_2}{h_6 - h_2}$

* get state 2 from $w_p = v dP$ & $h_1 \langle \text{sat liq} \rangle$

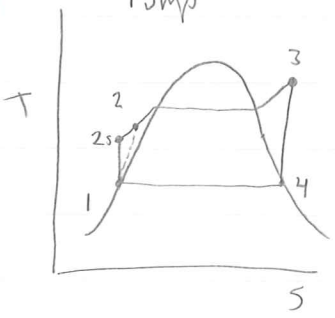
E. Losses

Turbine

$$\eta_t = \frac{w_{t,actual}}{h_3 - h_{4s}}$$



Pump

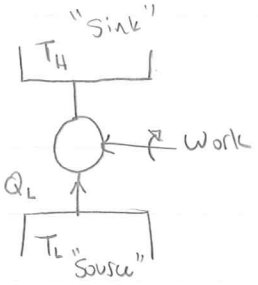


$$\eta_p = \frac{h_{2s} - h_1}{w_{p,actual}}$$

IV Refrigeration cycles

A: Vapor compression cycles

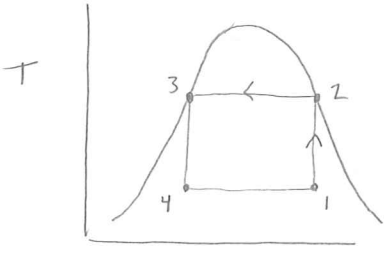
1) introduction

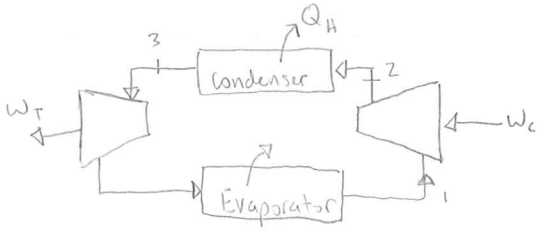


Goal: transfer heat from a low temp "source" to a high temp "sink"

- 2 possible outcomes
  1) desired output is Q_L "refrigerator, AC"
  2) desired output is Q_H "heat pump"

• design a ~~vapor~~ carnot vapor compression cycle





Note: expansion from 3-4 inside done with a turbine is a bad idea

- expansion 3-4 will produce little work

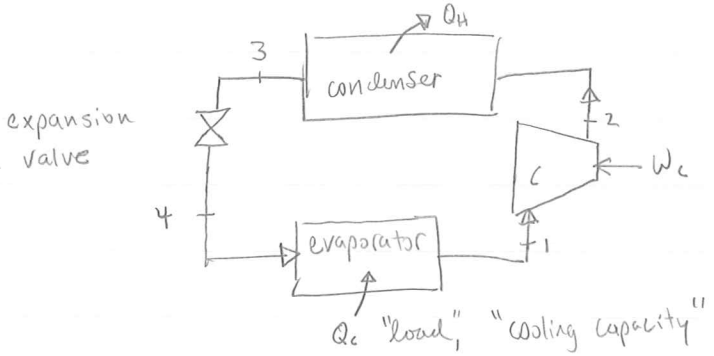
compression process is inside the dome

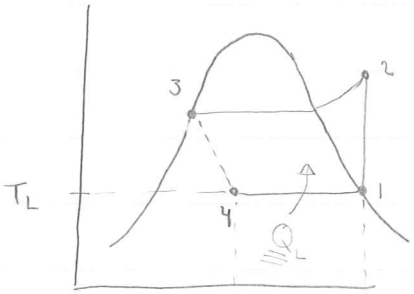
Exam 2: 10/22 (F), 10/25 (M), or 10/27 (W)

Notes 10-11-10

Brayton, Rankine, refrigeration

ii) ideal vapor compression Refrigeration cycle





(1-2) isentropic compression

(2-3) const. pressure heat rejection

(3-4) throttling process • adiabatic $q_4 - \cancel{w_4}^{\,0} = h_4 - h_3$ irreversible

(4-1)

iii) measures of performance

"coefficients of performance" COP, β

• refrigeration system $COP_R = \frac{q_L}{w_c}$ (β)

• heat pump system $COP_{HP} = \frac{q_H}{w_c}$ (β')

- energy efficiency Ratio, EER

• refrigeration system EER = $\frac{\text{cooling (Btu/hr)}}{\text{power input (watts)}}$

• heat pump " = $\frac{\text{heating (Btu/hr)}}{\text{pwr input (watts)}}$

Notes 10/11/10

iii) continued

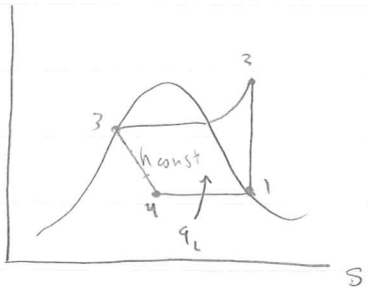
SEER ↑ seasonably adjusted $= 13 \Rightarrow COP_{HP} \approx 3.5$

- capacity $\frac{\text{cooling}}{\text{time}}$ (ie watts) Common units, 1 "TON" (cooling to freeze 1 ton H_2O in 1 day $= 3.52$ kW $= 12{,}000$ BTU/hr

iv) given: ideal vapor compression cycle

- Working fluid - "R12"
- $P_L = 0.1$MPa (evap) $P_H = 2.5$MPa (condenser)

Find COP, $\dot{m}_R$ for 1 ton of cooling



State 1 $P_1 = 0.1$ MPa $x_1 = 1$ $h = 174$ kJ/kg $T = -30°C$ $s = .7170$ kJ/kg-K

State 3 $x_3 = 0$ $P = 2.5$MPa $\Rightarrow h = 125$ $T = 84°C$

Compressor: $s_1 = s_2 = .7170$ $P_2 = 2.5$MPa $\Rightarrow h_2 = 232$ $T_2 = 102°C$

$\cancel{q_2}^{\,0} - {}_1w_2 = h_2 - h_1$ $w_c = h_1 - h_2 = -58$ kJ/kg

Expansion valve: (3-4) $h_3 = h_4 = 125$ kJ/kg ${}_4q_1 - \cancel{{}_4w_1}^{\,0} = h_1 - h_4$

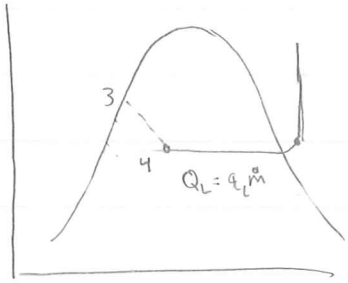
${}_4q_1 = 99$ kJ/kg

$COP_R = \frac{q_L}{w_c} = .845$

$\dot{Q}_L = 1\,TON = \dot{m}_R q_L$ $\dot{m}_R = \frac{\dot{Q}_L}{q_L} = 1\,\text{Ton}\left(\frac{3.25\,\text{kW}}{\text{Ton}}\right)\left(\frac{\text{kg}}{99\,\text{kJ}}\right)\left(\frac{1\,\text{kJ/s}}{1\,\text{kW}}\right)$

$\boxed{\dot{m}_R = .0714\ \text{kg/s}}$

iv)



iv) Working fluids

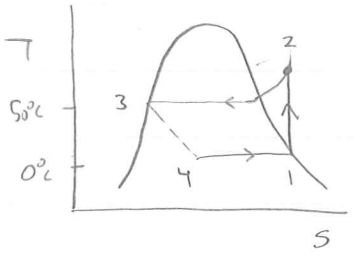
- principle refrigerants are halogenated hydrocarbons
- CFC
  - dichlorodifluoromethane CCl_2F_2
    or R12, (ASHRAE)

- due to concerns with ozone layer, CFC's were banned (they are very stable)

- HCFC monochlorodifluoromethane CHC_lF_2 or R22 (ASHRAE), freon 22
- HFC $C_2H_4F_2$ termed R134a (book) tetrafluoroethane
- pentafluoroethane F_5C_2H, R125

blend: 85% R125 + 15% R134a $\Rightarrow$ R422

Example: heat pump $T_{condenser} = 50°C$ $T_{evap} = 0°C$



$T_3 = 50°C$

Soln R12 State 1: $X = 1$ $T_1 = 0°C$

$h_1 = 187.5$ $s_1 = .6965$ State 3 $X_3 = 0$

$T_3 = 50°C$ $P_3 = 1.219$ MPa $h_3 = 84.94$

Compressor work $q - w_2 = h_2 - h_1$ $s_1 = s_2$ $P_2 = P_3 = 1.219$ MPa

$\Rightarrow h_2 = 211.95$

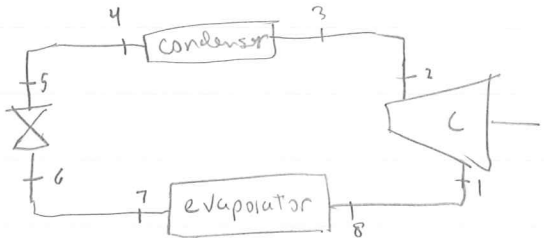
$q_H = q_{23} = h_3 - h_2 = 127$ kJ/kg $COP_{HP} = \frac{q_H}{w_L} = 5.20$

	R12	R22	R134a
P_2	1.219 MPa	1.94	1.34
T_2	56.7°C	72.7°C	55.4°C
w_2	22.42 kJ/kg	34.3	31.6
q_H	127.0 kJ/kg	176.4	158.5
COP	5.2	5.143	5.01

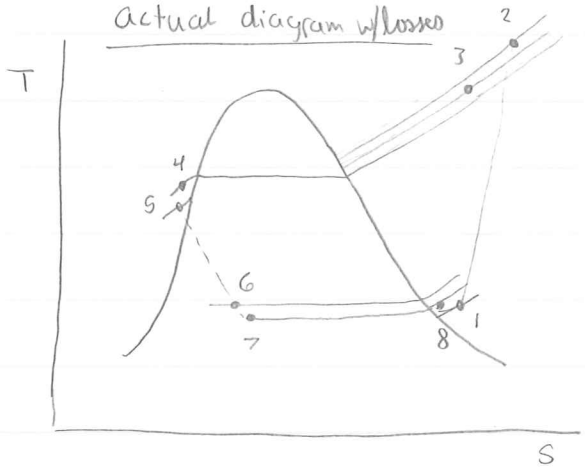
V) losses

Major losses : • Friction • Finite ΔT between refrigerant & environment

• heat transfer losses



actual diagram w/losses



Notes
10-15-10

last of material to be on exam (started with Brayton cycle)

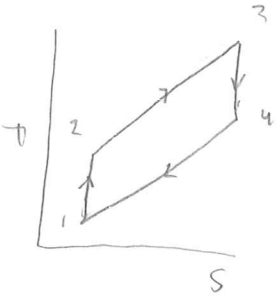
typically 2 rankine, Brayton, refrigeration

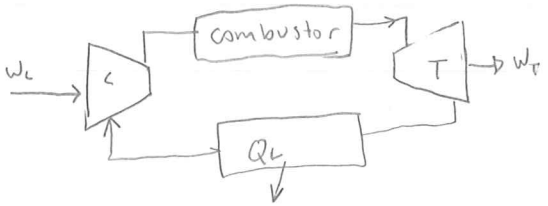
- working fluids, direction of cycles

A) Vapor compression cycle

B) air-standard refrigeration cycle : Objective : produce a refrigeration cycle based on brayton cycle

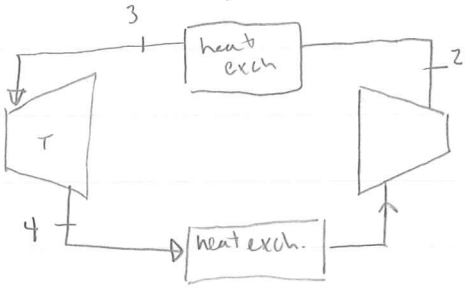
• Brayton cycle for power

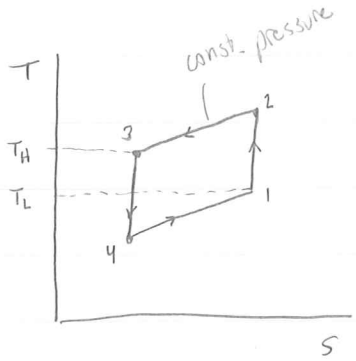




Notes 10-15-10

i) refrigeration cycle



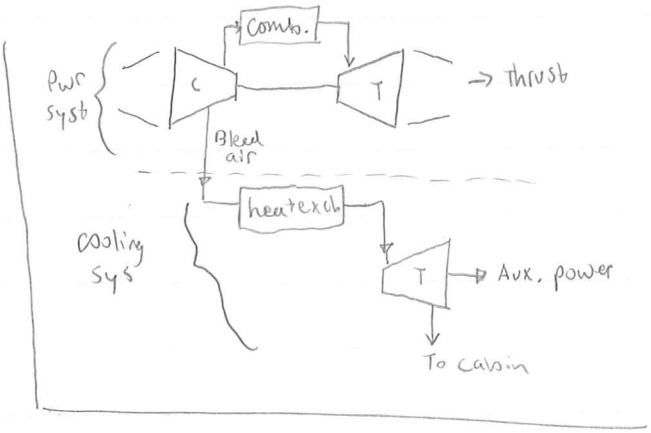


$$COP = \frac{\dot{Q}_L}{\dot{W}_{net}} = \frac{\dot{Q}_L}{\dot{W}_T + \dot{W}_c} \qquad Q_L = \dot{m}(h_1 - h_4) = \dot{m} c_p (T_1 - T_4)$$

ii) cycle example

- since Air is working fluid, this system can be operated as an open loop

ex: aircraft cabin cooling



example using T/s diagram above

$P_1 = 140 kPa \quad P_2 = 420 kPa$

$T_1 = 270 kPa \quad T_3 = 320°K$

$\dot{V}_1 = 1 m^3/s$

Find $\dot{W}_{net}$, $\dot{Q}_{in}$, COP

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{k-1/k} = 270 \left(\frac{420}{140}\right)^{.4/1.4} = 369.7k$$

Turbine: (3~4) $T_3 = 320 k \quad T_4 = \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}} = 320 \left(\frac{140}{420}\right)^{0.4/1.4} = 234 k$

$$\dot{W}_{net} = \dot{W}_T + \dot{W}_c = \dot{m}\left(c_p (T_3 - T_4) + C_1 (T_1 - T_2)\right)$$

$$\dot{m} = \rho_1 \dot{V} \qquad \rho_1 = \frac{P_1}{RT_1} = \frac{140k}{(.287)(270)} \qquad \dot{m} = 1 m^3/s \left(1.807 kg/m^3\right) \qquad \dot{m} = 1.807 kg/s$$

$$\dot{W}_{net} = (1.807)(1.004)(320 - 234 + 270 - 369.7) = -24.3 kW$$

$$COP = \frac{\dot{Q}_{in}}{\dot{W}_{net}} \qquad \dot{Q}_{in} = \dot{m} c_p (T_1 - T_4) = 65.82 kJ/s$$

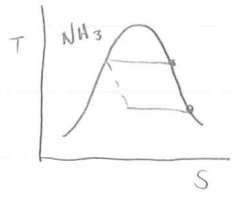
$COP = 7.71$

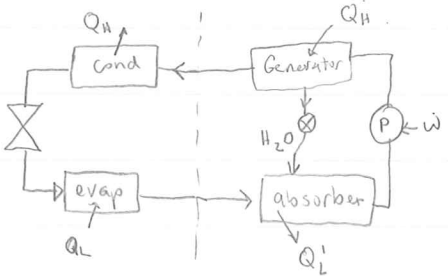
Notes
10-15-10

C. absorbsion refrigeration: Goal reduce work into compressor by pumping a liquid instead of vapor

method use a 2 component system

example: ammonia - water system





absorber: low P NH_3 combined w/ water to make liquid, Rxn is exothermic.

Pump: pump NH_3-H_2O mixture, work is small since pure liquid

Generator: separates ammonia from water by adding Q_H'. Q_H' can be low-grade heat

$$COP = \frac{Q_L}{\cancel{W_P} + Q_H'}$$

ALL CYCLES DONE

VI Mixtures

A) Ideal gas mixtures

1) mole & mass fractions

Define mass fraction, mf_i $\quad mf_i = \frac{m_i}{m_t}$ ← total mass of mixture

Define mole fraction; y_i $\quad y_i = \frac{n_i}{n}$; $\quad \sum y_i = 1$

Average MW, molecular weight:

$$MW = \frac{m}{n} = \frac{1}{n}\sum_i m_i = \frac{1}{n}\sum_i n_i MW_i \qquad \boxed{MW = \sum_i y_i MW_i}$$

Example; Air — 78% N_2, 21% O_2, 1% Argon } by mole

$$MW_{AIR} = \frac{0.78 \text{ kmoles } N_2}{\text{kmoles air}}\left(28 \frac{kg}{kmol\ N_2}\right) + (.21)(32) + (.01)(40)$$

$MW_{AIR} = 28.96$ kg/kmol of mixture

— conversion of mass & mole fractions:

$$mf_i = \frac{m_i}{m} = \frac{n_i MW_i}{\sum_i n_i MW_i} = \ldots \qquad \boxed{\frac{y_i MW_i}{MW}}$$

2) Ideal Gas Models

- consider 2 models of an ideal gas system

i) dalton model assumes: } ideal gas
- no interaction between gas molecules
- total molecular $\forall$ << container volume

- each gas in mixture behaves as if it were the only gas at the system T & $\forall$

Notes cont.
10-18-10

ie. $\boxed{A \& B}$ $\equiv$ $\boxed{A}$ + $\boxed{B}$

$P, T, \forall$ $\quad$ $T, \forall, P_A$ $\quad$ $T, \forall, P_B$

$n = n_A + n_B$ AND $P_A \forall = n_A R_u T$ where $\boxed{R_u = 8.314 \frac{kJ}{}}$

$P_B \forall = n_B R_u T$ $\quad$ $\frac{P\forall}{R_u T} = \frac{P_A \forall}{R_u T} + \frac{P_B T}{R_u T} \Rightarrow P = P_A + P_B$ Total pressure

partial pressures

$\therefore \boxed{P = \Sigma_i P_i}$

P: Total system pressure; $\Sigma_i P_i$: Sum of partial pressure

$\boxed{PV = NR_u T}$

$\boxed{R = \frac{R_u}{MW}}$

Notes
10-20-10

i) Dalton model $\boxed{P = \sum_i P_i}$

ii) Amagat Model assumes:
- no interaction b/w gas molecules
- total molecular volume << container $\forall$
- each gas constituent behaves as if it were the only gas at the system P & T

$\boxed{n \; A \& B} \equiv \boxed{n_A \; A} + \boxed{n_B \; B}$

$P, T, \forall$ $\quad$ $P, T, \forall_A$ $\quad$ $P, T, \forall_B$

$n = n_A + n_B$ $\quad$ $P\forall_A = n_A R_u T$, $P\forall_B = n_B R_u T$ $\quad$ $\frac{P\forall}{R_u T} = \frac{P\forall_A}{R_u T} + \frac{P\forall_B}{R_u T} \Rightarrow \forall = \forall_A + \forall_B$

Note. Dalton. $P_A = \frac{n_A R_u T}{\forall}$ $\quad$ $\frac{P_A}{P} = \frac{\frac{n_A R_u T}{\forall}}{\frac{n R_u T}{\forall}} = \frac{n_A}{n} = y_A$ so $\boxed{P_i = y_i (P)}$

Amagat: $\forall_A = \frac{n_A R_u T}{P}$ $\quad$ $\frac{\forall_A}{\forall} = \frac{\frac{n_A R_u T}{P}}{\frac{n R_u T}{P}}$ $\quad$ $\frac{n_A}{n} = y_A$ so $\boxed{\frac{n_i}{n} = y_i}$

* mole fraction is the same as volume fraction

3) u, H, & S relations for an ideal gas mixture

Internal energy & enthalpy

- recall $u = u(T)$; $h = h(T)$ for ideal gases
- dalton - each gas behaves as if alone

$$u = u_A + u_B \ldots = \sum_{i=1}^{N} u_i$$

$$H = H_A + H_B + \ldots = \sum_{i=1}^{N} H_i \quad \text{where } N = \text{total \# species}$$

— or —

$$n\bar{u} = \sum_i n_i \bar{u}_i$$

($\bar{u}_i$: per kmol; $\frac{kJ}{kmol\ i}$; $n\bar{u}$: $\frac{kJ}{kmol\ mixture}$)

$$\boxed{\bar{u} = \sum_{i=1}^{N} y_i \bar{u}_i \qquad \bar{h} = \sum_{i=1}^{N} y_i \bar{h}_i}$$

- $\bar{u}_i$ & $\bar{h}_i$ are evaluated @ system T

Now

$$\bar{c}_p = \frac{d\bar{h}}{dT} \qquad \bar{c}_v = \frac{d\bar{u}}{dT}$$

$$\frac{d\bar{u}}{dT} = \frac{d(\bar{y}_A u_A)}{dT} + \frac{d(y_B u_B}{dT} + \ldots$$

$$= y_A \frac{d\,\bar{u}_A}{dt} + y_B \frac{d(\bar{u}_B)}{dt} + \ldots$$

$$\Rightarrow \boxed{\bar{c}_v = \sum_{i=1}^{N} y_i \bar{c}_{v_i} \qquad \bar{c}_p = \sum_{i=1}^{N} y_i \bar{c}_{p_i}}$$

On a mass basis $u = \sum_{i=1}^{N} n_i \bar{u}_i = \sum_{i=1}^{N} \quad u = \sum_{i=1}^{N} \frac{M_i}{MW_i} \bar{u}_i$

But $\frac{\bar{u}_i}{MW_i} = u_i \left(\frac{kJ}{kg\ i}\right)$ $\qquad mu = \sum_{i=1}^{N} m_i u_i$

$$u = \sum_{i=1}^{N} m f_i u_i \; ; \quad h = \sum_{i=1}^{N} m f_i h_i$$

$$\boxed{c_v = \sum_{i=1}^{N} m f_i c_{v\,i} \qquad c_p = \sum_{i=1}^{N} m f_i c_p}$$

Notes 10-20-10
Wednesday

Entropy $S = s(T, P)$

$\Rightarrow$ entropy of a species is calculated at system T & P_i

$$s_i = s(T, P_i)$$

e.g. $$(s_2 - s_1)_i = \int_1^2 C_{p_i} \frac{dT}{T} - R_i \ln\left(\frac{P_{i,2}}{P_{i,1}}\right)$$

$$(\bar{s}_2 - \bar{s}_1)_i = \int_1^2 \bar{C}_{p_i} \frac{dT}{T} - R_u \ln\left(\frac{P_{i_2}}{P_{i_1}}\right)$$

As before:

$$\bar{s} = \sum_{i=1}^{N} y_i \bar{s}_i \qquad s = \sum_{i=1}^{N} m f_i s_i$$

Notes 10-25-10

4) Systems of constant composition

Constant or fixed composition $\Rightarrow$ y_i for a species is the same at each state $\therefore$ $\Delta\bar{u} = \bar{u}_2 - \bar{u}_1$

$$\Delta\bar{u} = \sum_i y_i \bar{u}_i(T_2) - \sum_i y_i u_i(T_1)$$

— OR —

$$\Delta\bar{u} = \sum_i y_i [\bar{u}_i(T_2) - \bar{u}_i(T_1)]$$

Note: for const. specific heats $\Delta\bar{u} = \sum_i y_i (c_{vi})(T_2 - T_1)$

OR

$$\Delta\bar{u} = c_{v_{mix}} (T_2 - T_1)$$

$$\Delta\bar{s} = \sum_i y_i [s_i(T_2, P_{i_2}) - s_i(T_1, P_{i_1})]$$

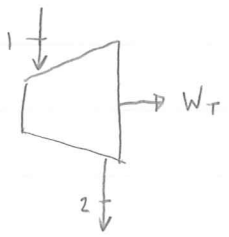
on a mass basis: $\Delta u = \sum_i m f_i [u_i\langle T_2\rangle - u_i\langle T_1\rangle]$

$$\Delta h = \sum_i m f_i [h_i\langle T_2\rangle - h_i\langle T_1\rangle]$$

Late to class - copy someone's notes

10-25

Example: Isentropic turbine



Given

$T_1 = 1000K$ $P_2 = 100kPa$

$P_1 = 800kPa$ $\dot{m} = 2kg/s$

Find: T_2, $\dot{W}_T$

i	Y_i
N_2	.66
CO_2	.17
H_2O	.17

Soln $k = \frac{\bar{C}_p}{\bar{C}_v}$ $\bar{C}_p = \sum_i Y_i \bar{C}_{p_i}$ $\bar{C}_p = (.66)(29.16 \frac{kJ}{kmol \cdot K}_{N_2})$

$\frac{kmol\ N_2}{kmol\ mix}$

$+.17(37.04) + (.17)(33.70)$

$\bar{C}_p = 31.27\ kJ/kmol\ mix\ K$

$C_v = (.66)(20.85 \frac{kJ}{kmol\ K}) + (.17)(28.73) + (.17)(25.52) = 29.98 \frac{kJ}{kmol_{mix} K}$

$k = \frac{\bar{C}_p}{\bar{C}_v} = 1.36$ $T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 577K$

$\cancel{Q} - \dot{W} = \dot{m}(h_2 - h_1)$ $W_T = \dot{m} C_{p_{mix}} (T_1 - T_2)$ or $\dot{W}_T = \dot{m} \sum_i m f_i C_{p_i} (T_1 - T_2)$

$C_{p\ mix} = \bar{C}_p / MW_{mixture}$ $MW_{mix} = \sum_i Y_i MW_i$

$MW_{mix} = .66(28 \frac{kJ}{kmol}) + .17(44) + .17(18)$ $MW_{mix} = 29\ kJ/kmol$

$C_{p,mix} = (31.27 \frac{kJ}{kmol\ K}) / 29\ kg/kmol = 1.078 \frac{kJ}{kmol \cdot K}$

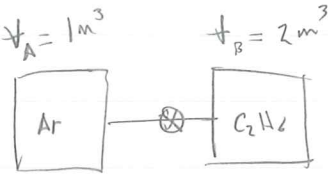
$\dot{W}_T = (2kg/s)(1.078\ kJ/kg\ K)(1000 - 577)$ $\boxed{\dot{W}_T = 912\ kJ/s}$

Example

Ideal gas mixing

$P_{Ar,1} = 300$ kPa $P_{C_2H_6,1} = 200$kPa insulated, $Q=0$

$T_{Ar,1} = 10°C$ $T_{C_2H_6,1} = 50°C$



open the valve, find T_2, P_2

Soln) 1st law $\cancel{Q_2}^{0} + \cancel{W_2}^{0} = U_2 - U_1 = \sum_i m_i(u_{i,2} - u_{i,1})$

$0 = m_{Ar} + C_{V_{Ar}}(T_2 - T_1) + m_{C_2H_6} C_{V_{C_2H_6}}(T_2 - T_1)$

$m_{Ar} = \frac{P_{Ar,1} V_{Ar}}{R_{Ar} T_{Ar,1}} = \frac{(300)(1m^3)}{(.2081)(283)} = 5.094$ $m_{C_2H_6} = \ldots = 4.479$ kg

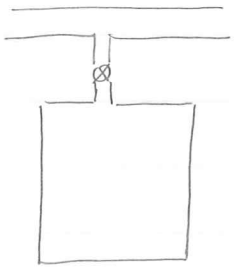
$0 = (5.094)(.312\ kJ/kg)(T_2 - 283) + (4.479)(1.490\ kJ/kg\cdot K)(T_2 - 323) \Rightarrow T_2 = 315.3K$

$P_2 = \frac{m_2 R_{mix} T_2}{\forall_T}$; $\forall_T = 3m^3$ $R_{mix} = \sum_i m f_i R_i$ $m f_{Ar} = \frac{5.094}{5.094 + 4.479} = .532$

$m f_{C_2H_6} = 1 - .532 = .468$ $R_{mix} = (.532)(.2081) + (.468)(.2765) = .240\ kJ/kg\cdot K$

$P_2 = \frac{(5.094 + 4.479)(.240\ kJ/kg\cdot K)(315.3)}{3m^3}$ $P_2 = 241.6$ kPa

Example



Given: State 1 (in tank)

$Y_{N_2} = 1$

$P_1 = 200 kPa$

$T_1 = 25°C$

CO_2 (inlet)

$Y_{CO_2} = 1$

$P_i = 1.2 MPa$

$T_i = 90°C$

State 2

$Y_{N_2} = Y_{CO_2} = 0.5$ a) find T_2 & P_2 such that $Y_{N_2,2} = Y_{CO_2,2} = 0.5$ assuming adiabatic (Fast)

soln 1st law around tank (unsteady)

$\frac{dE}{dt} = \dot{Q}_{cv}^{\,0} - \dot{W}_{cv}^{\,0} + \dot{m}_{in} h_{in} - \dot{m}_o^{\,0} h_o \qquad E = U \Rightarrow \frac{dU}{dt} = \dot{m}_{in} h_{in}$

$\int_1^2 d(mu) = \int_1^2 \dot{m}_{in} h_{in} dt \qquad m_2 u_2 - m_1 u_1 = m_{in} h_i$

Since problem is given on a molar basis, look at 1st law on a molar basis

$n_2 \bar{u}_2 - n_1 \bar{u}_1 = n_i \bar{h}_i$ const specific heats

$n_2 \bar{C}_{v_2} T_2 - n_1 \bar{C}_{v_1} T_1 = n_i \bar{C}_{P CO_2} T_i$ For final mixture $n_2 = n_1 + n_i$

Since equal mol fractions at state 2, $\Rightarrow n_i = n_1$

$2 n_1 \bar{C}_{v_2} T_2 - n_1 \bar{C}_{v,N_2} T_1 = n_1 \bar{C}_{P,CO_2} T_i$ Need $\bar{C}_{v_2}$ $\bar{C}_{v_2} = \sum_i y_i \bar{C}_{vi}$

$\bar{C}_{v_2} = Y_{N_2} \bar{C}_{v,N_2} + Y_{CO_2} \bar{C}_{v,CO_2} = .5 C_{v_{N_2}} + .5 C_{v_{CO_2}}$

$\therefore C_{v,N_2}(T_2 - T_1) + \bar{C}_{v,CO_2} T_2 = \bar{C}_{P CO_2} T_i$

$28 \frac{kg}{kmol} (.7448 \frac{kJ}{kg\,K})(T_2 - 298) + (44 \frac{kg}{kmol})(.6529 \frac{kJ}{kg\,K})(T_2) = 44 \frac{kg}{kmol} (.848 \frac{kJ}{kg\,K})(363\ K)$

$\Rightarrow \boxed{T_2 = 396.5\ K}$

Ex continued

$$P_2 = \frac{n_2 R_u T_2}{\forall} \qquad n_2 = 2n_1 \qquad n_1 = \frac{P_1 \forall_1}{R_u T_1} = \frac{200\text{kPa}\ \ 0.1\text{m}^3}{8.314\ \frac{\text{kJ}}{\text{mol·k}}\ (298\text{k})}$$

$n_1 = .00807$ kmol $\Rightarrow n_2 = .0161$ kmol $\Rightarrow P_2 = 532$ kPa

b) w/ valve closed, tank is cooled to $T_3 = 25°C$ Find ${}_2Q_3$

1st law:

$${}_2Q_3 - \cancel{{}_1W_3}^{\,0} = n_2 \bar{C}_{v_2} (T_3 - T_2)$$

– OR –

$${}_2Q_3 = n_{CO_2} \bar{C}_{v CO_2} (T_3 - T_2) + n_{N_2} \bar{C}_{v N_2} (T_3 - T_2)$$

$$= \left[.00807(44)(.6529) + (.00807)(28)(.7448) \right] (298 - 396.5)$$

$${}_2Q_3 = -39.4 \text{ kJ}$$

c) find entropy generated from 1→3

2nd law $\quad \frac{dS}{dt} \cong \dot{m}_{in} \dot{s}_{in} - \cancel{\dot{m}_o s_o}^{\,0} + \frac{\dot{Q}}{T_0} + \dot{S}_{Gen}$ $\quad$ $\dot{m}$ changed to molar basis

$$\int_1^3 \frac{dS}{dt} = \int_1^3 \dot{n}_{in} \bar{s}_{in} + \int_1^3 \frac{\dot{Q}}{T} + \int_1^3 \dot{S}_{gen}$$

$$n_3 \bar{s}_3 - n_1 \bar{s}_1 = n_i \bar{s}_i + \frac{{}_2Q_3}{T_0} + S_{Gen} \qquad n_3 \bar{s}_3 = n_{CO_2} \bar{s}_{CO_2,3} + n_{N_2} \bar{s}_{N_2,3}$$

$n_1 \bar{s}_1 = n_{N_2} \bar{s}_{N_2,1}$ & $n_i \bar{s}_i = n_{CO_2} \bar{s}_{CO_2,i}$

$$n_{CO_2} (\bar{s}_{CO_2,3} - \bar{s}_{CO_2,i}) + n_{N_2} (\bar{s}_{N_2,3} - \bar{s}_{N_2,1}) - \frac{{}_2Q_3}{T_0} = S_{Gen}$$

$$(\bar{s}_{N_2,3} - \bar{s}_{N_2,1}) = \bar{C}_p \ln\left(\frac{T_3}{T_1}\right) - R \ln\left(\frac{P_{N_2,3}}{P_{N_2,1}}\right) \qquad P_{N_2,3} = y_{N_2,3} P_3$$

$$P_3 = P_2 \left(\frac{T_3}{T_2}\right) = 532\text{ kPa} \left(\frac{298}{396.5}\right) = 400\text{kPa}$$

$$P_{N_2,3} = \tfrac{1}{2}(400) = 200\text{kPa} \qquad P_{N_2,1} = 200\text{kPa} \qquad T_3 = 25°C \qquad T_1 = 25°C$$

$$\Rightarrow \bar{s}_{N_2,3} - \bar{s}_{N_2,1} = 0 \qquad s_{CO_2,3} - s_{CO_2,1} = \bar{C}_{p CO_2} \ln\left(\frac{T_3}{T_1}\right) - R_u \ln\left(\frac{P_3}{P_1}\right)_{CO_2}$$

$\frac{298}{363}$ $\qquad \left(\frac{\frac{1}{2}(400)}{1200}\right)$

$$= 7.856\ \frac{\text{kJ}}{\text{kmol·k}}$$

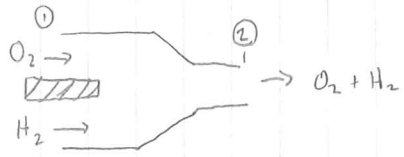
$$S_{Gen} = (.00807)\text{kmol}\left(7.586\ \frac{\text{kJ}}{\text{kmol·k}}\right) - \frac{39.4\text{ kJ}}{298\text{k}}$$

$$= \boxed{.1934\ \text{kJ/k}}$$

Notes 10-27-10

5) Ideal gas mixing

Example: adiabatic mixing chamber



O_2: $P_1 = 1\,MPa$ $T = 500k$ $\dot{m} = 1\,kg/s$

H_2: $P_1 = 1\,MPa$ $T = 300k$ $\dot{m} = 0.1\,kg/s$

$P_2 = 1\,MPa$

Find: T_2, S_{gen}

Sol'n

1st law $\cancel{\dot{Q}}^{\,0} - \cancel{\dot{W}}^{\,0} = \dot{m}_o h_o - \dot{m}_i h_i = \dot{m}_{O_2}(h_1 - h_2)_{O_2} + \dot{m}_{H_2}(h_1 - h_2)_{H_2}$

assume const specific heats

$0 = \dot{m}_{O_2} c_{p_{O_2}} (T_1 - T_2) + \dot{m}_{O_2} c_{p_{O_2}} (T_1 - T_2)_{H_2}$

$0 = (1\,kg/s)(.9216)(500 - T_2) + (0.1)(14.2)(300 - T_2) \Rightarrow \boxed{T_2 = 378\,k}$

2nd law $\frac{d\cancel{S_{CV}}^{\,0}}{dt} = \sum_i \dot{m}_i s_i - \sum_i \dot{m}_o s_o + \sum \cancel{\frac{\dot{Q}}{T}}^{\,0} + \dot{S}_{Gen}$

$S_{Gen} = \dot{m}_{H_2}(s_2 - s_1)_{H_2} + \dot{m}_{O_2}(s_2 - s_1)_{O_2}$

$(s_2 - s_1)_{H_2} = c_{p_{H_2}} \ln\left(\frac{T_2}{T_1}\right)_{H_2} - R \ln\left(\frac{P_{H_2,2}}{P_{H_2,1}}\right)$ ← partial pressures

$(s_2 - s_1)_{O_2} = c_{p_{O_2}} \ln\left(\frac{T_2}{T_1}\right)_{O_2} - R \ln\left(\frac{P_{O_2,2}}{P_{O_2,1}}\right)$

Point 2 — $P_i = y_i P$ $\quad y_{H_2} = \frac{n_{H_2}}{n_{mix}} = \frac{n_{H_2}}{n_{H_2} + n_{O_2}} = \frac{\dot{m}_{H_2}/MW_{H_2}}{\frac{\dot{m}_{H_2}}{MW_{H_2}} + \frac{\dot{m}_{O_2}}{MW_{O_2}}}$

$y_{H_2} = \frac{(0.1\,kg/s)/(2\,kg/kmol)}{\frac{0.1}{2} + \frac{1.0}{32}} = .615$ $\quad y_{O_2} = 1 - y_{H_2} = .385$

$P_{H_2,2} = y_{H_2} P_2 = .615\,MPa$ $\quad P_{O_2,2} = y_{O_2} P_2 = .385\,MPa$

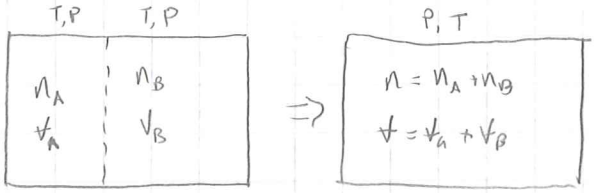
$(s_2 - s_1)_{H_2} = (14.2)\ln\left(\frac{378}{300}\right) - (4.12)\ln\left(\frac{.615}{1}\right) = 5.28\ kJ/kg\,K$

$(s_2 - s_1)_{O_2} = \left(.9216\ \frac{kJ}{kg\,k}\right)\ln\left(\frac{378}{300}\right) - (.2598)\ln\left(\frac{0.385}{1}\right) = -0.0098\ kJ/kg\,K$

$S_{gen} = (.1\,kg/s)(5.28\ kJ/kg\,k) + (1\,kg/s)(-.0098\ kJ/kg\,k) = \boxed{.518\ kJ/kg} > 0$

Notes 10-27-10

Example closed system, adiabatic



2nd law fixed mass: $S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}^{0} + S_{Gen}$

$$S_{Gen} = n_A(\bar{s}_2 - \bar{s}_1)_A + n_B(\bar{s}_2 - \bar{s}_1)_B$$

$$(\bar{s}_2 - \bar{s}_1)_A = \bar{c}_{p_A} \cancel{\ln\left(\frac{T_2}{T_1}\right)_A^{0}} - R\ln\left(\frac{P_{A,2}}{P_{A,1}}\right) \qquad P_{A,1} = P;\ P_{A_2} = y_A P$$

$T_1 = T_2$

$$(\bar{s}_2 - \bar{s}_1)_A = -\bar{R}_u \ln(y_A) \quad \text{AND} \quad (\bar{s}_2 - \bar{s}_1)_B = -R_u \ln(y_B)$$

$$S_{Gen} = -n_A R_u \ln y_A - n_B R_u \ln y_B \quad \Rightarrow \quad S_{Gen} = -R_u \sum_{i=1}^{n} n_i \ln y_i$$

notes: $\cdot\ y_i < 1$, $\therefore$ S_{Gen} always positive

S_{Gen} always the same for any 2 gasses (same y_i) except they must be dissimilar

Notes

11-1-2010

B) Gas / Vapor Mixtures (Psychometrics)

- study of water vapor & dry air
- treat both gases as ideal gases

1) definitions, for each component

$$P_A = \frac{m_A R_A T}{\forall}$$

$$P_v = \frac{m_v R_v T}{\forall}$$

} At system T & $\forall$

Total $\boxed{P = P_A + P_v}$

- humidity ratio, ω

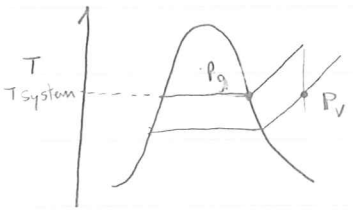
$$\omega = \frac{m_v}{m_A} \left\{ \frac{\text{kg water}}{\text{kg air}} \right\}$$ AKA Specific humidity

note: $\omega = \frac{P_v \forall / R_v T}{P_A \forall / R_A T} = \frac{m \omega_v P_v}{m \omega_A P_A}$

$$\frac{m\omega_v}{m\omega_A} = .622$$

$$\boxed{\omega = 0.622 \frac{P_v}{P_A} = .622 \frac{P_v}{P - P_v}}$$

- consider the T-s diagram for the water vapor in mixture



P_v = partial pressure of H_2O vapor

$P_g \equiv$ sat. vapor pressure @ system T (eg, for T = 25°C, P_g = 3.169 kPa)

- define relative humidity ϕ:

$$\phi = \left. \frac{P_v}{P_g} \right|_{T,P}$$ note: $\phi = \frac{P_v}{P_g} = \frac{P_v/P}{P_g/P} = \frac{y_v}{y_g|_{T,P}}$

- ϕ changes with system T even for a fixed amount of H_2O vapor in system

Note $\phi = \frac{\omega P_A}{0.622 P_g}$

2) System properties - for ideal gas mixtures:

$$H = \sum_{i=1}^{N} m_i h_i$$

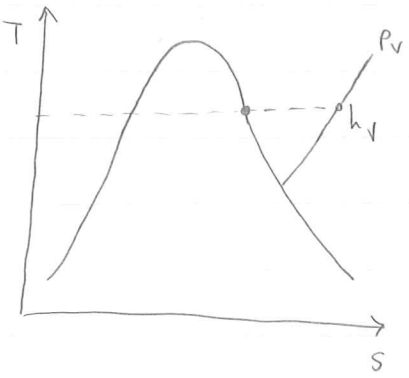
for ideal gas mixture $H = \sum_{i=1}^{N} m_i h_i$

for a water vapor & air mixture $H = m_a h_a + m_v h_v$

$$\frac{H}{m_a} = h_a + \omega h_v$$

↖ "enthalpy per kg of dry air"

Note:



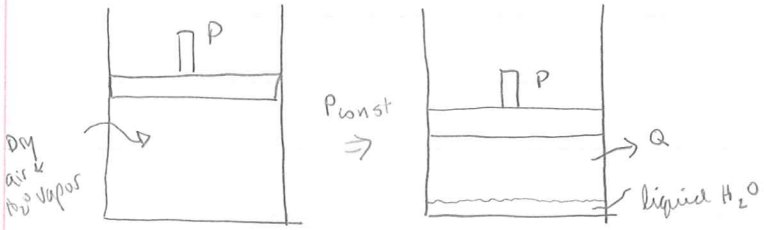
- since for an ideal gas, $h = h(T_{only})$

$\Rightarrow h_v \cong h_g(T_{system})$

$\Rightarrow \frac{H}{m_A} = h_a + \omega h_g(T_{system})$

3) Dew Point: Temperature at which water will begin to condense out of the air as sys temperature is lowered at a const total P

Consider the following

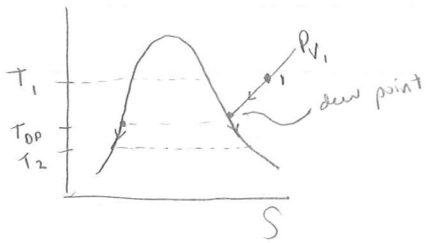


$Y_{V_2} < Y_{V_1}$

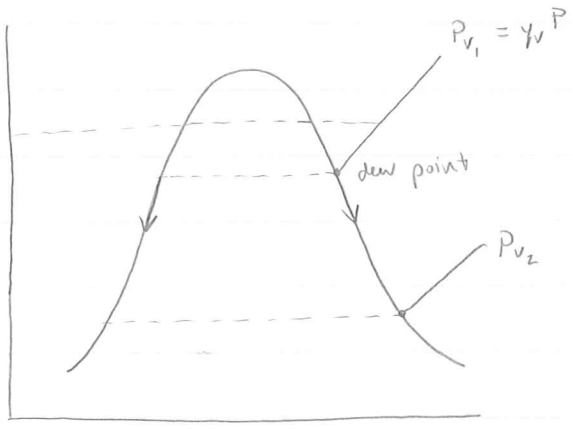
$P_v = Y_v P$

(0)

if liquid water is present, the system is saturated



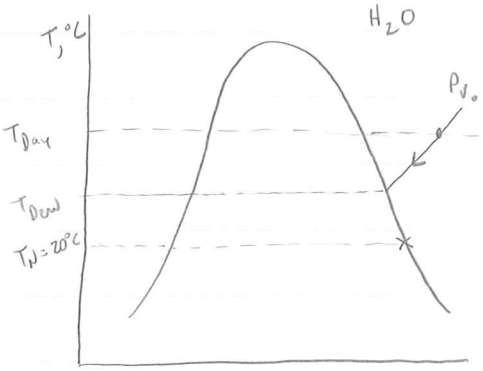
Friday 14.28, D.33



Examples:

i) summer day $T_D = 25°C$ $P_D = 0.1 MPa$ $\phi = 80\%$

" night $T_N = 20°C$ $P_D = 0.1 MPa$



Find: Dew will form? , % H_2O condensed

$\phi = 80\% = \left.\frac{P_v}{P_g}\right|_{T,P}$ $P_g(25°C) = 3.169$ kPa

$P_{v,D} = 0.8(3.169\ kPa) = 2.535$

T_{Dew} = T when $P_g = P_{v_D} = 2.535$ kPa (interpolate) $T_{DP} = 21.3°C$

$T_{Night} < T_{DP} \Rightarrow$ **Dew will form**

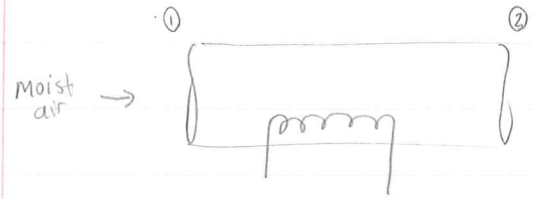
$$\frac{m_{v,night}}{m_{v,day}} = \frac{\frac{P_{v_N} \cancel{\forall}}{R_v T_N}}{\frac{P_{v_D} \cancel{\forall}}{\cancel{R_v} T_D}} \quad \frac{P_{v_N}}{P_{v_D}} \cdot \frac{T_D}{T_N}$$

$P_{v_N} = P_g(20°C) = 2.339$ kPa

$$\frac{m_{v,N}}{m_{v,D}} = \frac{2.339}{2.54} = .937$$

% condensed out $= 1 - .937 =$ **6.34%**

(i) heating system



$P_1 = 101\ kPa$ $\quad P_2 = P_1$

$T_1 = 10°C$ $\quad T_2 = 25°C$

$\phi_1 = 50\%$

sol'n $\quad \dot{Q} - \cancel{\dot{W}} = \sum_o \dot{m}h - \sum_i \dot{m}h \qquad Q = \dot{m}_{a_2}h_{a_2} + \dot{m}_{v_2}h_{v_2} - \dot{m}_{a_1}h_{a_1} - \dot{m}_{v_1}h_{v_1}$

$\dot{m}_{a_1} = \dot{m}_{a_2}$ divide by $\dot{m}_{air}$ $\quad \frac{\dot{Q}}{\dot{m}_a} = h_{a_2} - h_{a_1} + \frac{\dot{m}_{v_2}}{\dot{m}_a}h_{v_2} - \frac{\dot{m}_{v_1}}{\dot{m}_a}h_{v_1}$

$\frac{kJ}{kg\ dry\ air}$

COM $\quad \dot{m}_{v_1} = \dot{m}_{v_2} \Rightarrow \omega_1 = \omega_2 \qquad = h_{a_2} - h_{a_1} + \omega_2 h_{v_2} - \omega_1 h_{v_1}$

$q = C_p(T_2 - T_1) + \omega(h_{v_2} - h_{v_1})$

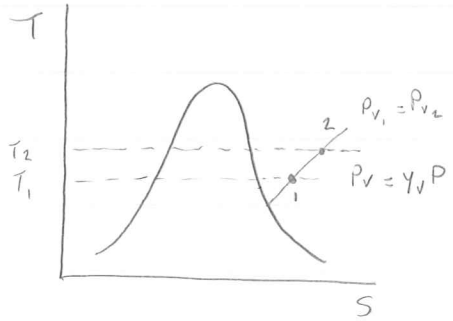
$h_{v_2} \to h_g\langle T_2\rangle$ $\quad h_{v_1} \to h_g\langle T_1\rangle$

$h_g(T_2) = 2547\ \frac{kJ}{kg}$

$h_g\langle T_1\rangle = 2519.8$

$\omega = .622\left(\frac{P_v}{P - P_v}\right) \qquad \phi_1 = .5 = \frac{P_{v_1}}{P_g\langle T_1\rangle} \qquad P_{v_1} = 0.5(1.228) = 0.614\ kPa$

$\omega_1 = 0.622\left(\frac{.614}{101 - .614}\right) \qquad \omega_1 = 0.00381$

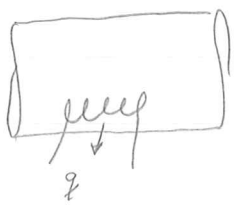


$q = (1.004\frac{kJ}{kg\,K})(15K) + (.0038)(2547.2 - 2519.8)$

$= 15.15\ kJ/kg_1$ dry air

find ϕ_2, $\phi_2 = \frac{P_{v_2}}{P_{g_2}\langle T_2\rangle} = \frac{.614}{3.169} = 19.4\%$

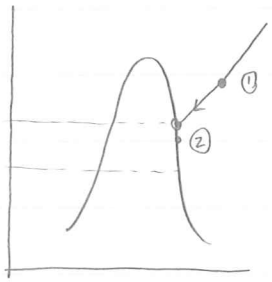
Ex 2) Now cool



$P_1 = 101\ kPa \quad T_1 = 10°C \quad \phi_1 = 50\% \quad P_g\langle T_1\rangle = 1.228\ kPa$

$P_{v_1} = 0.614\ kPa \quad \omega_1 = .00381$

$T_2 = .01°C$



$P_{v_1} = .614 kPa$ @ $P_1 = P_g = .614 \Rightarrow T_{dp} = 0.07°C$

$T_2 < T_{DP} \Rightarrow$ water will condense

Note $\dot{m}_{v_2} \neq \dot{m}_{v_1} \Rightarrow \omega_2 \neq \omega_1$

C.O.M $\quad \dot{m}_\ell = \dot{m}_{v_1} - \dot{m}_{v_2} = \dot{m}_a(\omega_1 - \omega_2)$

Notes 11-5-10

$\omega_1 = 0.00381 \quad \omega_2 = 0.622\left(\frac{P_{v_2}}{1 - P_{v_2}}\right) \quad P_{v_2} = P_g(T_2) = .6113$

$\omega_2 = 0.00379 \quad \dot{m}_\ell = \dot{m}_a(0.00381 - .00379) \quad \dot{m}_\ell = 1.24 \times 10^{-5}\, \dot{m}_a$

* how much q needs to be removed ?

$$\dot{Q} = \dot{m}_{a_2} h_{a_2} + \dot{m}_{v_2} h_{v_2} + \dot{m}_\ell h_\ell - \dot{m}_{a_1} h_{a_1} - \dot{m}_{v_1} h_{v_1}$$

$\dot{m}_{a_1} = \dot{m}_{a_2}$

$$\frac{\dot{Q}}{\dot{m}_a} = q = h_{a_2} - h_{a_1} + \omega_2 h_{v_2} - \omega_1 h_{v_1} + \frac{\dot{m}_\ell}{\dot{m}_a} h_\ell$$

$\dot{m}_\ell = \dot{m}_{v_1} - \dot{m}_{v_2}$
$= \dot{m}_a(\omega_1 - \omega_2)$

$$q = c_{p_a}(T_2 - T_1) + \omega_2 h_{v_2} - \omega_1 h_{v_1} + \omega_1 - \omega_2 h_\ell$$

$$q = c_{p_a}(T_2 - T_1) + \omega_2 h_g\langle T_2\rangle - \omega_1 h_g\langle T_1\rangle + " \quad "$$

$h_\ell = h_f\langle T_2\rangle$

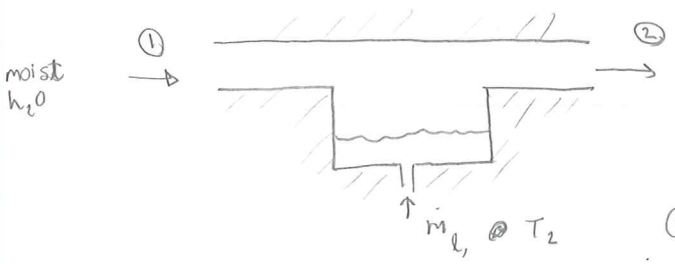
$h_g\langle T_2\rangle = 2501.3 \quad h_g\langle T_1\rangle = 2519.8$

$h_f(T_2) = 0.001 \qquad q = -10.12\ ^{KJ}/_{kg}$ dry air

4) determine humidity level of Humidity

- how can humidity be measured based on P & T only ?

a) adiabatic Saturation temp, T_{as} consider the following Expt:



Goal; find ω_1 assume adiabatic

$$\dot{m}_{a_2} h_{a_2} + \dot{m}_{v_2} h_{v_2} = \dot{m}_{a_1} h_{a_1} + \dot{m}_{v_1} h_{v_1} + \dot{m}_\ell h_\ell \qquad (1)$$

Cons. mass — $\dot{m}_{a_1} = \dot{m}_{a_2} \rightarrow$

$$\dot{m}_{v_1} + \dot{m}_\ell = \dot{m}_{v_2} \rightarrow \text{divide (1) by } \dot{m}_a$$

$$h_{a_2} + \omega_2 h_{v_2} = h_{a_1} + \omega_1 h_{v_1} + (\omega_2 - \omega_1) h_\ell$$

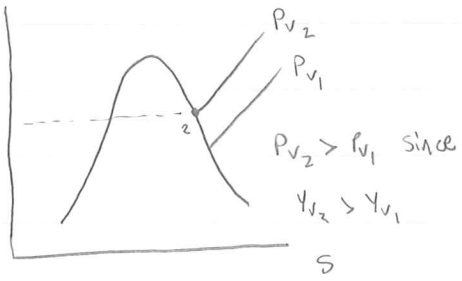
noting that h_2 is saturated (with an 's')

$$\omega_1 (h_{v_1} - h_\ell) = h_{a_{2s}} - h_{a_1} + \omega_{2s} (h_{v_{2s}} - h_\ell)$$

$h_{v_1} = h_g\langle T_1 \rangle$ $\quad h_\ell = h_f\langle T_2 \rangle$ $\quad h_{v_{2s}} = h_g\langle T_{2s} \rangle$ $\quad h_\ell = h_f\langle T_2 \rangle$

$$\omega_1 = \frac{C_{p_a} (T_{2s} - T_1) + \omega_{2s} h_{fg}\langle T_{2s} \rangle}{h_g\langle T_1 \rangle - h_f\langle T_{2s} \rangle}$$

$$\omega_{2s} = .622 \left(\frac{P_{v_{2s}}}{P - P_{v_2}} \right) \qquad P_{v_{2s}} = P_g\langle T_{2s} \rangle$$



Example $T_1 = 25^\circ C$ $\quad T_2 = 15^\circ C$ $\quad P_1 = P_2 = 101 kPa$

Find ω_1 & ϕ for $T_2 = T_{as}$

Soln @ T_1: $h_g = 2547$ $\quad T_2$: $h_f = 62.99$ $\quad h_{fg} = 2466$ $\quad P_g\langle T_2 \rangle = 1.7051$

$$\omega_{2s} = 0.622 \left(\frac{1.7051}{101 - 1.7051} \right) = .01068$$

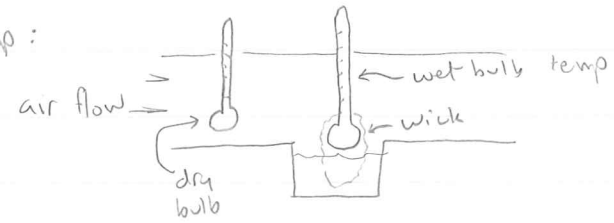
ω_1 $\quad \omega_1 = \dfrac{(1.004)(-10) + (.01068)(2466)}{(2547 - 62.99)}$ $\quad \omega_1 = .006434$

ϕ_1? $\quad \phi_1 = \dfrac{P_{v_1}}{P_g\langle T_1 \rangle}$; $P_g\langle T_1 \rangle = 3.109 kPa$ $\quad \omega_1 = .622 \left(\dfrac{P_{v_1}}{P - P_{v_1}} \right) \Rightarrow P_{v_1} = 1.034 kPa$

$$\phi_1 = 32.6\%$$

b) wet & dry bulb temperature

- at STP a 'wet bulb' temp approximates the adiabatic sat. temp:



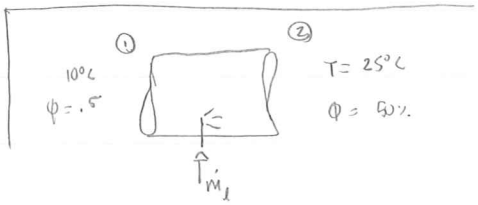
"Sling psychrometer" 55° wet 75° dry

Ex. requirement for heating a building $\dot{v} = 1\ m^3/s$ of dry air

$T = 25°C$ $P = 100\ kPa$ $\phi = 50\%$

outside air $T = 0°C$ 100kPa, $\phi = 50\%$

find $\dot{m}_l$ & $\dot{Q}$



$\dot{m}_l = \dot{m}_{v_2} - \dot{m}_{v_1} = \dot{m}_a(\omega_2 - \omega_1)$ $\dot{v}_2 = 1\ m^3/s$ dry air

State 1: $\omega = .622\left(\frac{P_{v_1}}{P - P_{v_1}}\right)$ $\phi = \frac{P_{v_1}}{P_g\langle T_1\rangle}$ $P_g\langle T_1\rangle = 1.2276 \Rightarrow P_{v_1} = .6138$ $\phi = .5$

$\omega = .622\left(\frac{.6138}{100 - .6138}\right)$ ω_2, by same process $\Rightarrow \omega_2 = .0100$

$\dot{m}_{a_1} = \dot{m}_{a_2}$ $\dot{m}_a = \frac{P_2 \dot{v}_2}{R_a T_2}$ $P_{a_2} = 100 - 1.5845$

$\dot{m}_l = 1.15\ ^{kg}/_{s}\ (0.0100 - .00384) = \boxed{.00706\ ^{kg}/_{s}}$

1st law $\dot{Q} - \dot{W}^{\circ} = \dot{m}_a h_2 + \dot{m}_{v_2} - \dot{m}_{a_1} h_{a_1} - \dot{m}_{v_1} h_{v_1} - \dot{m}_l h_l$

$\frac{\dot{Q}}{\dot{m}_a} = c_{pa}(T_2 - T_1) + \omega_2 h_g\langle T_2\rangle - \omega_1 h_g\langle T_1\rangle - (\omega_2 - \omega_1) h_f\langle T_2\rangle$

$\frac{\dot{Q}}{\dot{m}_a} = 30.3\ ^{kJ}/_{kg\ dry\ air}$ $\dot{Q} = (30.3)(1.15\ ^{kg}/_{s}) = \boxed{34.9\ kW}$

Example Rigid tank

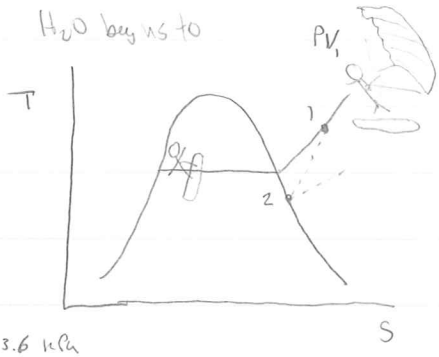
Remove Q until $T_2 = 25°C$

160°C 400kPa
$2 m^3$ $\phi = 20\%$

Find a) T at which condens. begins

b) m_l collected

Soln recall definition of Dew point: T at which H_2O begins to condense @ P



But $\forall$ & m_V constant until liquid forms

$\Rightarrow$ condensation begins A T when $v_{V_1} = v_g$

$$v_{V_1} = \frac{R_v T_1}{P_{V_1}} \qquad P_{V_1} = \phi_1 P_g(T_1) = .2(617.8\,kPa) = 123.6\,kPa$$

$v_{V_1} = 1.62\ m^3/kg$ $\quad v_g = v_{V_1} @ T_{cond} = 101°C$

$$m_l = m_{V_1} - m_{V_2} = m_a(\omega_1 - \omega_2) \qquad \omega_1 = .622 \frac{P_{V_1}}{P - P_{V_1}} = \ldots .278$$

State 2 $P_{V_2} = P_{sat}(T_2) = 2.339\,kPa$ (saturated)

$$\omega_2 = .622 \underbrace{\frac{P_{V_2}}{(P_2 - P_{V_2})}}_{P_{A_2}} \qquad \text{for fixed } m_a \quad \frac{P_{a_1}\forall_1}{R_a T_1} = \frac{P_{a_2}\forall_2}{R_a T_2}$$

$$P_{a_2} = P_{a_1}\left(\frac{T_2}{T_1}\right) \Rightarrow \omega_2 = .622 \frac{(2.339)}{187} = .00778$$

$$m_a = \frac{P_a \forall_1}{R_a T_1} = 4.45\,kg = m_l = 4.45\,kg\,(0.278 - .00778) = 1.2\,kg$$

1st law $Q_2 = U_2 - U_1$

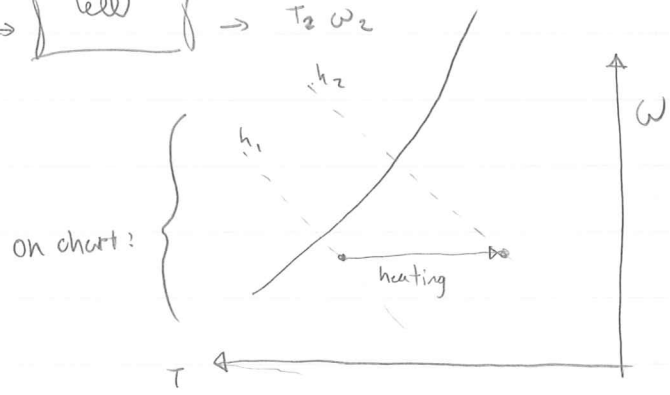
Notes
11-10-10

Ex

i) Simple heating:

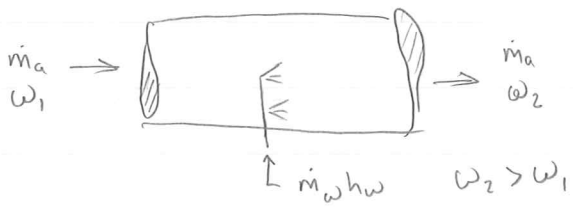
$$\dot{Q} = \dot{m}_a h_{a2} + \dot{m}_v h_{v2} \cdots$$
$$= \dot{m}_a (h_2 - h_1)$$

where $h = h_a + \omega h_v$



ii)

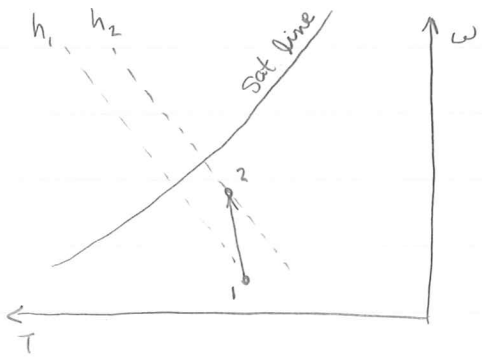
Simple humidification



$\omega_2 > \omega_1$

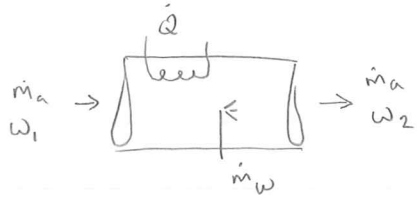
Copy analysis

$$h_2 = h_1 + (\omega_2 - \omega_1) h_\omega$$



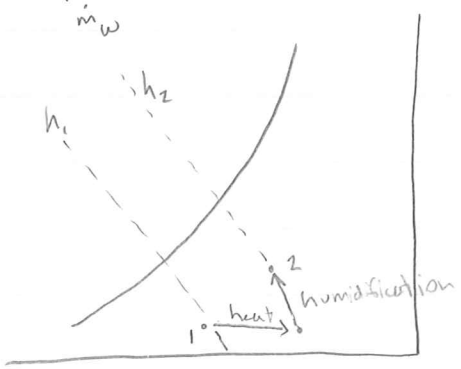
iii) heat & humidification

$$\dot{Q} - \dot{\omega} = \dot{m}_a h_{a2} + \dot{m}_v h_{v2} - \dot{m}_a h_{a1} - \dot{m}_v h_{v1} - \dot{m}_\omega h_\omega$$

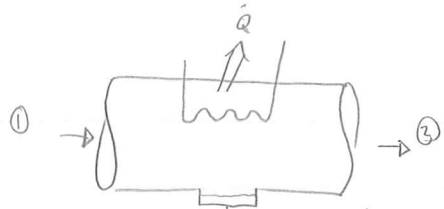


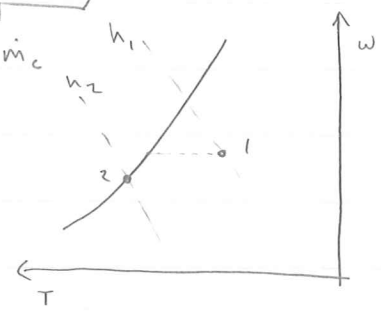
$$\frac{\dot{Q}}{\dot{m}_a} = q = h_{a2} - h_{a1} + \omega_2 h_2 - \omega_1 h_1 - (\omega_2 - \omega_1) h_\omega$$

$$q = h_2 - h_1 - (\omega_2 - \omega_1) h_\omega$$



iv) cooling & dehumidification





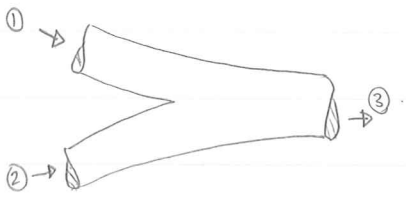
$$\dot{Q} - \cancel{\dot{W}}^{\,0} = \dot{m}_a h_{a2} + \dot{m}_v h_{v2} + \dot{m}_c h_c - \dot{m}_a h_{a1} - \dot{m}_v h_{v1}$$

$$q = \underbrace{(h_{a2} + \omega_2 h_{v2})}_{h_2} - \underbrace{(h_{a1} + \omega_1 h_{v1})}_{h_1} + (\omega_1 - \omega_2) h_c$$

$$q = h_2 - h_1 + (\omega_1 - \omega_2) h_c$$

Due monday : D 39, 14.107

Example adiabatic mixing



T, ω, ϕ = ?

1st law $\dot{Q} - \dot{W} = \dot{m}_{a3} h_3 + \dot{m}_{v3} h_3 - \dot{m}_{a2} h_{a2} - \dot{m}_{v2} h_{v2} - \dot{m}_{a1} h_{a1} - \dot{m}_{v1} h_{v1}$

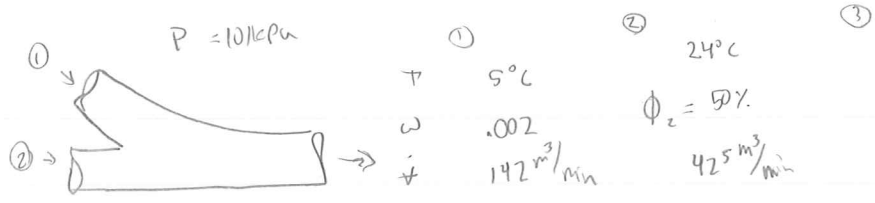
$$0 = \dot{m}_{a3}(h_3 + \omega_3 h_3) - \dot{m}_{a2}(h_{a2} + \omega_2 h_{v2}) - \dot{m}_{a1}(h_{a1} + \omega_1 h_{v1})$$

(h_3 ↑ f T_3)

Cons mass: $\dot{m}_{a3} = \dot{m}_{a2} + \dot{m}_{a1}$ $\dot{m}_{v3} = \dot{m}_{v2} + \dot{m}_{v1}$

$$\boxed{\dot{m}_{a3}\omega_3 = \dot{m}_{a2}\omega_2 + \dot{m}_{a1}\omega_1}$$

Notes 11-12-10



Soln cons mass $\dot{m}_{a_1} + \dot{m}_{a_2} = \dot{m}_{a_3}$ $\dot{m}_{v_2} + \dot{m}_{v_1} = \dot{m}_{v_3}$

$\dot{m}_{a_1}\omega_1 + \dot{m}_{a_2}\omega_2 = \dot{m}_{a_3}\omega_3$ $\omega_3 = \dfrac{\dot{m}_{a_1}\omega_1 + \dot{m}_{a_2}\omega_2}{\dot{m}_{a_3}}$

$\dot{m}_{a_1} = \rho_{a_1}\dot{v}_{a_1}$ $\rho_{a_1} = \dfrac{P_{a_1}}{R_a T_1}$ $P_{a_1} = P - P_v$ $\omega_1 = .622\,\dfrac{P_{v_1}}{P - P_{v_1}}$

$\omega_1 = .002 \Rightarrow P_{v_1} = .344$ kPa $P_a = 101 - .344 = 100.7$ kPa

$\rho_a = \dfrac{100.7}{(.287)(278)} = 1.26\ kg/m^3$ $\dot{m}_{a_1} = 178.9$ kg/min

$\dot{m}_{a_2} = \rho_{a_2}\dot{v}_{a_2}$ $P_{v_2} = \phi_2 P_g(T_2) = .5\,(2.985) = 1.493$ kPa

$\rho_{a_2} = \dfrac{(101 - 1.493)}{(.287)(297)} = 1.167\ kg/m^3$ $\Rightarrow \dot{m}_{a_2} = 496.2$ kg/min

$\dot{m}_{a_3} = 178.9 + 496.2 = 675$ kg/min $\omega_3 = (178.9)(.002) + (496.2)(.622)\left(\dfrac{1.493}{101 - 1.493}\right)$

$\omega_3 = .0074$

1st law $\dot{Q} - \dot{W}^{\circ} = \dot{m}_{a_3}h_{a_3} + \dot{m}_{v_3}h_{v_3} - \dot{m}_{a_2}h_{a_2} - \dot{m}_{v_2}h_{v_2} - \dot{m}_{a_1}h_{a_1} - \dot{m}_{v_1}h_{v_1}$

$0 = \dot{m}_{a_3}(h_{a_3} + \omega_3 h_{v_3}) - \dot{m}_{a_2}(h_{a_2} - \omega_2 h_{v_2}) - \dot{m}_{a_1}(h_{a_1} + \omega_1 h_{v_1})$

$\Rightarrow \dot{m}_{a_3}h_3 = \dot{m}_{a_2}h_2 + \dot{m}_{a_1}h_1$ $h_1 = h(\omega_1, T_1)$ psyc. chart 10 kJ/kg

$h_2 = h(\phi_2, T_2)$ 48

$h_3 = \dfrac{1}{\dot{m}_{a_3}}(\dot{m}_{a_2}h_2 + \dot{m}_{a_1}h_1) = 37.94$ kJ/kg dry air

$T_3 = f(h_3, \omega_3) \cong 19°C$

$\omega_3 = .0074$

EXAM III has now been covered

11-12-18

VII Chemical Reactions (combustion)

① ②

Fuel + oxidizer → products

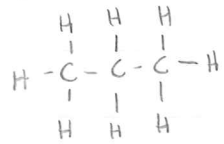
reactants ↓ release energy

- hydrocarbon fuels C_xH_y
- "oxygenated" fuels nitromethane, solid rocket propellant
- oxidizers → O_2, "Air"

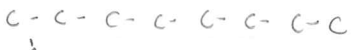
Exam III Mixtures, psychometrics, (will not use psychometric chart 11-15-10

1) Pure hydro carbons
   - single component fuels, "Neat" fuels
   i) paraffins
      - C_nH_{2n+2}
      - chain structure (straight or branched)
      - single carbon bonds (saturated)
        - ex: Propane, C_3H_8
        - ex: Octane C_8H_{18}

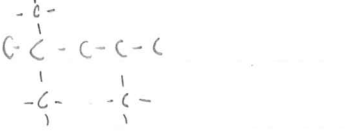
propane



n-octane



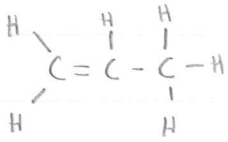
iso-octane



ii) OLEFIN
- C_nH_{2n}
- chain structure
- double bonded carbon (unsaturated)

ex: propene C_3H_6

Propane



iii) Alcohols
- $C_nH_{2n+1}OH$
- "Oxygenated" fuels

ex: methanol, CH_3OH

2) real fuels:

examples: gasoline, Diesel fuel, Jet "A", kerosine
- gasoline MW = 110 kg/kmol

$\frac{H}{C} = 1.87$

Thermodynamic representation:

$C_xH_y \Rightarrow \frac{y}{x} = 1.87 \quad 12x + y = 110 \Rightarrow x = 7.93 \quad y = 14.83$

$C_{7.93}H_{14.83}$

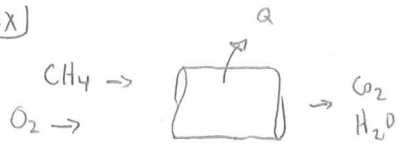
B. Combustion Stoichiometry

1) Species conservation

Ex: complete combustion of methane

combustion RXN: $\underbrace{CH_4 + 2O_2}_{\text{reactants}} \rightarrow \underbrace{a\,CO_2 + b\,H_2O}_{\text{products}}$

ex)



C balance: $1 = a, \Rightarrow a = 1$

H balance: $4 = 2b \Rightarrow b = 2$

O_2 balance: $2 = 1 + \frac{1}{2}(2)$ ✓

11-15-10

* define: complete combustion:
  - fully oxidized products
  (for HC fuels, products are CO_2 & H_2O)

2) stoichiometry (relative amts of fuel & oxidizer)

* define: stoichiometric Mixture - exact amt of fuel & oxidizer for complete combustion

* define fuel/air ratio

$$F/A = \frac{\text{mass fuel}}{\text{mass air}}$$

$\frac{F}{A} = .0641$

$\frac{A}{F} = 15.6$

ex: propane & air

find: stoichiometric air ratio

soln) air, typically 79% N_2, 21% O_2 (by volume)

$\therefore$ 1 kmol O_2 to $\frac{79}{21} = 3.76$ kmol N_2

$$C_3H_8 + a(O_2 + 3.76\,N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

C: $3 = b$

H_2: $4 = c$

O_2: $a = b + \frac{1}{2}c = 5$

N_2: $3.76a = d = 18.8$

$$\frac{F}{A} = \frac{1\text{ kmol } C_3H_8 \left(\overbrace{12(3)+8}^{MW\ F}\right)}{5(4.76)\underbrace{(29\ ^{kg}/_{kmol})}_{MW\ air}}$$

Notes 11-16-10

Exam 3 questions,
- mixtures
- psychometrics

2) stoichiometry

Define: equivalence ratio, ϕ

$$\phi = \frac{(F/A)_{actual}}{(F/A)_{stoichiometric}}$$

$\phi > 1 \Rightarrow$ fuel rich

$\phi < 1 \Rightarrow$ fuel lean

Define: % theoretical air $= \frac{1}{\phi} \times 100$

Define: % excess air $= \left(\frac{1}{\phi} - 1\right) \times 100$

Example: Propane & air

* case 1 stoichiometric $\frac{F}{A}$

in mols → $C_3H_8 + a(O_2 + 3.76N_2) \rightarrow b\,CO_2 + c\,H_2O + d\,N_2$

C: $3 = b$

H_2: $4 = c$

O_2: $a = b + \frac{1}{2}c = 5$

N_2: $d = 3.76a = 18.8$

$$\left.\frac{F}{A}\right|_{st} = \frac{1(3(12)+8)}{5(4.76)(29)} = .0641$$

* case 2

$C_3H_8 + 10(O_2 + 3.76N_2)$ ← "actual"

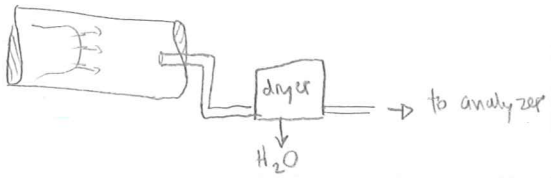
find ϕ

$$\phi = \frac{\left.\frac{F}{A}\right|_{act}}{\left.\frac{F}{A}\right|_{st.}} = \frac{3(12)+8}{10(4.76)(29)} = .032$$

$\phi = 0.5$

3) PRODUCT ANALYSIS

dry analysis: water is removed from products before analysis



Example C_8H_{18} & air

dry basis product analysis

	Vol %
CO_2	10.2
CO	4.7
CH_4	2900 ppm = .29%

N_2, O_2, H_2O ← (others)

Find: F/A

Actual Rxn:

$a C_8H_{18} + b(O_2 + 3.76N_2) \rightarrow 10.2\,CO_2 + 4.7\,CO + c\,O_2 + 0.29\,CH_4 + d\,N_2 + e\,H_2O$

C: $8a = 10.2 + 4.7 + .29$

H: $18a = .29(4) + 2e$

O_2: $b = 10.2 + 4.7\left(\frac{1}{2}\right) + c + \frac{1}{2}e$

N_2: $3.76b = d$

also $10.2 + 4.7 + c + .29 + d = 100\%$

Solve $\Rightarrow b = 22.2$, $a = 1.90$

$$\left.\frac{F}{A}\right|_{actual} = \frac{1.9(8(12)+18)}{22.2(4.76)(29)} = .0707$$

Notes continued
11-17-10

alternatively:

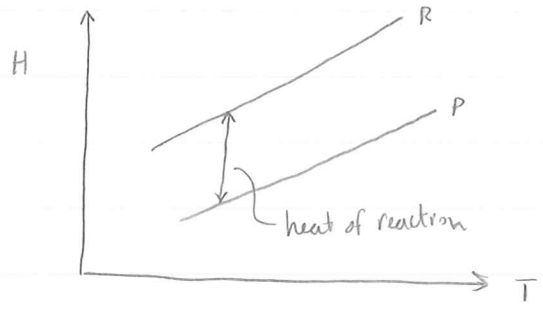
$C_8H_{18} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cCO + dO_2 + eCH_4 + fN_2 + gH_2O$

C:
H:
O:
N:
} solve

then $Y_{CO} = \frac{c}{b+c+d+e+f}$

$Y_{CO_2} = \frac{b}{c+d+e+f}$

define: heat or enthalpy of combustion
≡ heat released when a process is done at constant T



Notes 11-29-10

due Wed - D.40, D.41

Exam III high 100
low 35
mean 74.4
STD. Dev. 18.9

C) 1st law for reaction systems

1) C.V. analysis (open system)

Reactants → Products

end points for thermodynamic calculations

$Q - W = H_P - H_R$

$Q - W = \sum_P n_i \bar{h}_i - \sum_R n_i \bar{h}_i$

i) heat of formation

To calculate the energy released from a combustion reaction, we must determine the enthalpy difference between products & reactants

∴ must use a common enthalpy reference state for all species

define: heat of formation

$\bar{h}_f^\circ$ ← std. conditions
↖ formation
per kmol

≡ heat of formation of species i at 298 K

≡ energy released (or absorbed) when a compound is from its elements at std. conditions

reference state:

$\bar{h}_f^\circ = 0$ for elements as they occur naturally

eg. $\bar{h}_f^\circ = 0$ for N_2, O_2, H_2, C

Table A.26

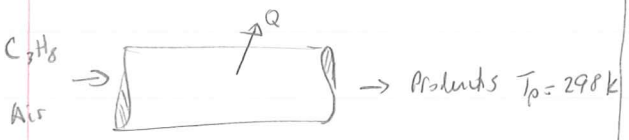
Notes 11-29-10

Example: Propane & Air

$T_p = T_R = 298K$

$Q - W = \sum_P n_i \bar{h}_i + \sum_R n_i \bar{h}_i$

note: $\bar{h}^\circ_{f\ liquid} = \bar{h}^\circ_{f\ gas} - \bar{h}_{fg}$



For stoich. conditions

$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.76)N_2$

$Q = \sum_P n_i \bar{h}_i - \sum_R n_i \bar{h}_i$

if a species is at 298K $\Rightarrow h_i = \bar{h}^\circ_{f\,i}$

$Q = \sum_P n_i \bar{h}^\circ_{f,i} - \sum_R n_i \bar{h}^\circ_{f\,i}$

$Q = 3\bar{h}^\circ_{f,CO_2} + 4\bar{h}^\circ_{f,H_2O} + 5(3.76)\bar{h}^\circ_{f,N_2} - \bar{h}^\circ_{f,C_3H_8} - 5\bar{h}^\circ_{f,O_2} - 5(3.76)\bar{h}^\circ_{f,N_2}$

($\bar{h}^\circ_{f,O_2}$ and $\bar{h}^\circ_{f,N_2}$ are 0)

$Q = 3(-393,520\ kJ/kmol\ CO_2) + 4(-241,820\ kJ/kmol\ (CO_2)) - 1(-103,850\ kJ/kmol\ C_3H_8)$ } A.26

($\frac{kmol\ CO_2}{kmol\ fuel}$)

$Q = -2.04(10^6)\ \frac{kJ}{kmol\ fuel}$

$Q = -4.64(10^4)\ kJ/kg\ fuel$

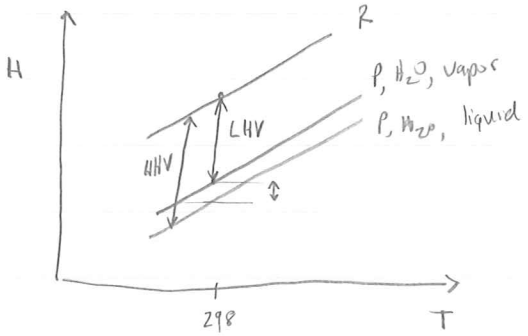
ii) define: heating value

heating value $\equiv -Q$ when $T_p = T_R = 298$ and complete combustion

"energy content"

$$HV \equiv \sum_R n_i \bar{h}^\circ_{fi} - \sum_P n_i \bar{h}^\circ_{f\,i}$$ complete combustion

- higher heating value, HHV
  HV with product H_2O in liquid state
- lower heating value, LHV
  HV with product H_2O in vapor state



Notes 12-1-2010

Example 1

Given CH_4

$LHV_{CH_4} = 50,016 \ kJ/kg$

Find $\bar{h}^\circ_{f,CH_4}$

Sol^N

Stoich $\rightarrow CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$

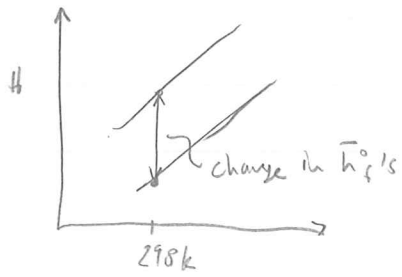
$LHV = \sum_R n_i \bar{h}^\circ_{f_i} - \sum_P n_i \bar{h}^\circ_{f_i}$ for complete combust.

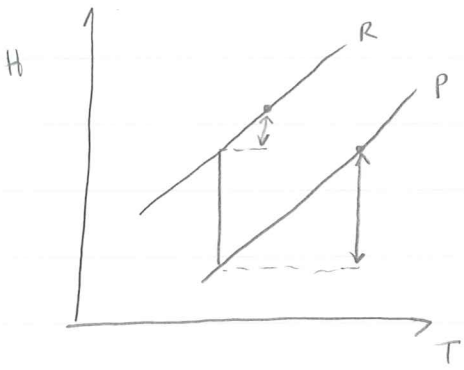
$LHV_{CH_4} = \bar{h}^\circ_{f_{CH_4}} + 2\bar{h}^\circ_{f_{O_2}} + 2(3.76)\bar{h}^\circ_{f_{N_2}} - \bar{h}^\circ_{f_{CO_2}} - 2\bar{h}^\circ_{f_{H_2O}} - 7.52\bar{h}^\circ_{f_{N_2}}$

$(50,016 \ kJ/kg) \times 16 \ kg/kmol = \bar{h}^\circ_{f_{CH_4}} - (-393,520 \ kJ/kmol) - 2(-241,820 \ kJ/kmol)$

$\Rightarrow \bar{h}^\circ_{f_{CH_4}} = \boxed{-76,900 \ kJ/kmol}$

(ii) Calculation of heat release for products & reactants @ arbitrary conditions





1st law for a CV analysis:

$$\bar{Q} - \bar{W} = \sum_P n_i (\bar{h}^\circ_{f_i} - \Delta\bar{h})_i - \sum_R n_i (\bar{h}^\circ_f + \Delta\bar{h})_i$$

where $\Delta\bar{h}_i = \bar{h}_i(T) - \bar{h}_i(298)$

$= \int_{T_{298}}^{T} \bar{c}_p \, dT$ ← in book, $\bar{h}_o$

Table A.18 - A.24

Example next pg.

12-1-2010

Ex

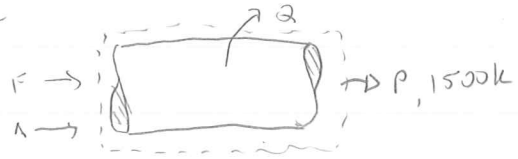
given: Propane & air

$T_{C_3H_8} = 25°C$ $T_{air} = 700K$ $\phi = 1$, complete combustion

$T_{products} = T_{flame} = 1500K$

Find: Q assume no w

Soln



$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.76)N_2$$

$$Q - W^{\circ} = \sum_P n_i(\bar{h}_f + \Delta\bar{h})_i - \sum_R n_i(\bar{h}_f + \Delta\bar{h})_i$$

$$Q = 3(\bar{h}_f^{\circ} + \Delta\bar{h})_{CO_2} + 4(\bar{h}_f^{\circ} + \Delta\bar{h})_{H_2O} + 5(3.76)(\cancel{\bar{h}_f^{\circ}} + \Delta\bar{h})_{N_2} - (\bar{h}_f^{\circ} + \cancel{\Delta\bar{h}}^{\circ})_{C_3H_8}$$
$$- 5(\cancel{\bar{h}_f^{\circ}} + \Delta\bar{h})_{O_2} - 5(3.76)(\cancel{\bar{h}_f^{\circ}} + \Delta\bar{h})_{N_2}$$

(it is at 298°k)

Products	$\bar{h}_f$ (kJ/kmol)	$\Delta\bar{h}$ (kJ/kmol)
CO_2	-393,520	(710,078 − 9364) = 61,714
H_2O	-241,820	48,095
N_2	0	38,405

Reactants		
C_3H_8	-103,850	0
O_2	0	$\bar{h}_{(700)} - \bar{h}_{(298)} = 12,502$
N_2	0	11,937

$$\bar{Q} = 3(-393,520 + 61,714) + 4(-241,827 + 48,095)$$
$$+ 5(3.76)(0 + 38,405) - 1(-103,850 + 0) - 5(0 + 12,502) - 5(3.26)(0 + 11,937)$$

$$\boxed{\bar{Q} = -1.23 \times 10^6 \text{ kJ/kmol } C_3H_8}$$

2) Fixed Mass Analysis (Closed System)

1st law for fixed mass

$$Q - W = \Delta U = U_P - U_R$$
$$= \Delta H - \Delta(PV)$$

But for ideal gases $PV = n\bar{R}T$ ∴ 1st law for fixed mass:

$$\boxed{\bar{Q} - \bar{W} = \sum_P n_i (\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_i - \sum_R n_i (\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_i}$$

$= \bar{R} = 8.314 \ kJ/kmol\,k$

12-3-10

Example:

fuel - gasoline, $m_f = 0.1kg$ oxidizer - air const. volume, stoich, complete comb.

$T_R = 298k$ $T_P = 2000k$ $P_i = 100kPa$

Find Q and P_f

Gasoline: $\frac{H}{C} = 1.87$ $MW = 110 \ kg/kmol$ $LHV = 44 \times 10^3 \ kJ/kg$

Soln need C_xH_y $\frac{y}{x} = 1.87$ $12x + y = 110$ $x = 7.93$ $y = 14.83$

$$C_{7.93} + H_{14.83} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

C: $b = 7.93$

H_2: $c = \frac{14.83}{2} = 7.415$

O_2: $a = b + \frac{1}{2}c = 11.64$

N_2: $d = 3.76a$

$$C_{7.93}H_{14.83} + 11.64(O_2 + 3.76N_2) \rightarrow 7.93CO_2 + 7.415H_2O + 11.64(3.76)N_2$$

$$\bar{Q} - \bar{W}^{\,0} = \sum_P n_i (\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_i - \sum_R n_i (\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_i$$

$$\bar{Q} = 7.93(\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_{CO_2} + 7.415(\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_{H_2O} + 3.76(11.64)(\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_{N_2}$$
$$- (\bar{h}_{f\,C_xH_y}^\circ + \Delta\bar{h} - \bar{R}T)_{C_xH_y} - 11.64(\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_{O_2} - 11.64(3.76)(\bar{h}_f^\circ + \Delta\bar{h} - \bar{R}T)_{N_2}$$

Need $\bar{h}_{f\,C_xH_y}^\circ$ have $LHV = \sum_R n_i \bar{h}_f^\circ - \sum_P n_i \bar{h}_{fi}^\circ$ (complete combustion)

$$44 \times 10^3 \ kJ/kg \times 110 \ kg/kmol) = \bar{h}_{f\,C_xH_y}^\circ - 7.93\,\bar{h}_{f\,CO_2}^\circ - 7.415\,\bar{h}_{f\,H_2O}^\circ$$

$$\Rightarrow \bar{h}_{f\,C_xH_y}^\circ = -73{,}777 \ kJ/kmol\,f$$

ex. continued)

$$\bar{Q} = 7.93(-393{,}520 + 91{,}362 - 8.314(2000))$$
$$+ 7.415(-241{,}827 + 72{,}619 - 8.314(2000))$$
$$+ 3.76(11.64)(\quad\quad\quad\quad)$$

$\bar{Q} = -1.99(10^6 \text{ kJ/kmol fuel})$

$Q = \bar{Q}\left(\frac{1 \text{ kmol}}{110 \text{ kg}}\right) = -1.81 \times 10^4 \text{ kJ/kg}$ $\quad\boxed{Q = -1810 \text{ kJ}}$

$P_f = \frac{n_p \bar{R} T_f}{\forall}$; $P_i = \frac{n_R \bar{R} T_i}{\forall}$ $\quad n_p = 7.93 + 7.415 + 3.76(11.64)$

$n_R = 1 + 11.64(4.76) = 56.4$

$P_{final} = P_i\left(\frac{n_p}{n_R}\right)\left(\frac{T_f}{T_i}\right) = 703 \text{ kPa}$

Notes
12-6-10

3) adiabatic flame temperature

- maximum flame temperature occurs for $\phi = 1$ (stoichiometric)
  - no work or heat transfer
  - complete combustion
- In practice, this maximum flame temp is not seen due to
  - losses (heat transfer)
  - dissociation eg $CO_2 \rightleftharpoons CO + \frac{1}{2}O_2$
    "endothermic" $\rightarrow$
- an "adiabatic" flame temperature is often calculated as a reference temperature & used as a "maximum"

a) calculation procedure

- for open system (ie, CV) $\not{Q}^{\circ} - \not{W}^{\circ} = \Delta H$

$\sum_P n_i(\bar{h}_f^{\circ} + \Delta\bar{h})_i = \sum_R n_i(\bar{h}_f^{\circ} + \Delta\bar{h})_i$ $\quad T_P$ is unknown $(T_P = T_{AFT})$

IF fuel, oxidizer & T_R are known: $\Rightarrow$ $\bar{h}_f^{\circ}$ reactants

$\Delta\bar{h}$ reactants

$\bar{h}_f^{\circ}$ products

unknown: $\Delta\bar{h}$ products

$\Rightarrow$ iterative problem

- for a fixed mass system (closed system)

$$\cancel{Q^{\circ}} - \cancel{W^{\circ}} = \Delta U$$

$$\sum_{P}\left(\bar{h}_f^{\circ} + \underbrace{\Delta\bar{h}}_{f(T_P)} - \underbrace{\bar{R}T}_{f(T_P)}\right)_i = \sum\left(\bar{h}_f^{\circ} + \Delta\bar{h} - \bar{R}T\right)_i$$

$\Rightarrow$ iterative problems

b) examples

i) methane & air (CH_4) given $\Phi = 1$ open system $T_R = 298\,K$

Find: AFT

Soln $\quad CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$

$$\sum_{P} n_i\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_i = \sum_{R} n_i\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_i$$

$$\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_{CO_2} + 2\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_{H_2O} + 7.52\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_{N_2} = \left(h_f^{\circ} + \Delta h\right)_{CH_4} + 2\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_{O_2} + 7.52\left(\bar{h}_f^{\circ} + \Delta\bar{h}\right)_{N_2}$$

Reactants:	$\bar{h}_f^{\circ}$	$\Delta\bar{h}$
CH_4	$-74{,}873$	
Products:		
CO_2	-393520	?
H_2O	-241820	?
N_2	0	?

$$\Delta\bar{h}_{CO_2} + 2\Delta\bar{h}_{H_2O} + 7.52\Delta\bar{h}_{N_2} = 802{,}303\ kJ$$

$T_P(K)$	LHS
2300	790,154
2400	834,292

interpolate

$T_P = 2328\,K$

ii) Redo i) but with O_2

$CH_4 + 2O_2 = CO_2 + 2H_2O$

$\sum_P n_i(\bar{h}_f^\circ + \Delta h)_i = \sum_R n_i(\bar{h}_f^\circ + \Delta h)_i$

$(\quad)_{CO_2} + 2(\quad)_{H_2O} = (\ /\ )_{CH_4} + 2(\ /\ )_{O_2}$

$\Delta\bar{h}_{CO_2} + 2\Delta\bar{h}_{H_2O} = 802,303 \text{ kJ}$

Note: same as last problem but N_2 is not present

T(K)	LHS
5200	800,544
5400	874,192

$T_{AFT} = 5214 \text{ K}$

iii) Methane & Air for Const $\forall$ (fixed mass) combustion

- $\phi = 1$ $\quad CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$
- $T_R = 298$

$\sum_P n_i(\bar{h}_f^\circ + \bar{\Delta h} - \bar{R}T)_i = \sum_R n_i(\bar{h}_f^\circ + \bar{\Delta h} - \bar{R}T)_i$

$(\ +\ -\ )_{CO_2} + 2(\ +\ -\ )_{H_2O} + 7.52(\ +\ -\ )_{N_2} =$

$(\ +\ -\ )_{CH_4} + 2(\ +\ -\ )_{O_2} + 7.52(\ +\ -\ )_{N_2}$

298K (CH4) · 298K (O2) · 298K (N2)

$\Delta\bar{h}_{CO_2} + 2\Delta\bar{h}_{H_2O} + 7.52\,\Delta\bar{h}_{N_2} - 87.46\,T_P = 776,239$

T (K)	h
2800	767,938
2900	804,188

$T_P = 2823 \text{ K}$

$T_{AFT}\big|_{P=const} < T_{AFT}\big|_{\forall=const}$

due to expansion work for const P problem

HW # 38 for Friday D. 48, 49

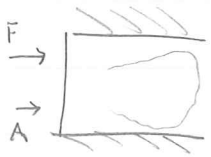
Exam 4 Friday after, 10:30-12:30 (12/17)

Example Jet A & air

Given: H/C = 1.911 MW = 166 kg/kmol $LHV|_{gaseous} = 43,200 \frac{kJ}{kg}$

$h_{fg}(fuel) = 270 \frac{kJ}{kg}$

- $T_{initial} = 25°$ for fuel ⇒ liquid
- constant P
- stoichiometric, complete combustion



Find: adiabatic flame temperature

$C_xH_y + \ldots \Rightarrow C_{11.9}H_{22.8} + a(O_2 + 3.76N_2) \rightarrow 11.9CO_2 + 11.4H_2O + 3.76aN_2$

$a = 17.6$

1st law $\sum_P n_i(\bar{h}_f^\circ + \Delta\bar{h})_i = \sum_R n_i(\bar{h}_f^\circ - \Delta\bar{h})_i$

$11.9(\bar{h}_f^\circ + \Delta\bar{h})_{CO_2} + 11.4(\bar{h}_f^\circ + \Delta\bar{h})_{H_2O} + 3.76(17.6)(\cancel{\bar{h}_f^\circ} + \Delta\bar{h})_{N_2} = (\bar{h}_f^\circ + \cancel{\Delta\bar{h}}^{\,0})_{C_xH_y}$

$+ 17.6(\cancel{\bar{h}_f^\circ}^{\,0} + \cancel{\Delta\bar{h}}^{\,0})_{O_2} + 3.76(17.6)(\cancel{\bar{h}_f^\circ}^{\,0} + \cancel{\Delta\bar{h}}^{\,0})_{N_2}$

need: $\bar{h}_f^\circ$ for C_xH_y. Have $LHV|_{Gaseous}$ ∴ $LHV|_{liquid} = LHV|_{gaseous} - h_{fg}(fuel)$

$LHV|_{liq} = 43,200 \frac{kJ}{kg} - 270 \frac{kJ}{kg} = 42,930 \frac{kJ}{kg}$

Now $LHV_l = \sum_R n_i\bar{h}_f - \sum_P n_i\bar{h}_f^\circ$ } complete combustion

$(42930 \frac{kJ}{kg} \times 166 \frac{kg}{kmol}) = \bar{h}_f^\circ - 11.9\bar{h}_{f\,CO_2}^\circ - 11.4\bar{h}_{f\,H_2O}^\circ$

use $\bar{h}_f^\circ$ for gaseous H_2O since $\equiv LHV$

$\Rightarrow \bar{h}_{f\,C_xH_y}^\circ = -313,348 \frac{kJ}{kmol}$

$11.9(-393,520 + \Delta\bar{h})_{CO_2} + 11.4(-241820 + \Delta\bar{h})_{H_2O} + 3.76(17.6)(\Delta\bar{h})_{N_2} = -313,348$

$11.9\Delta\bar{h}_{CO_2} + 11.4\bar{h}_{H_2O} + 66.18\Delta\bar{h}_{N_2} = 7.126 \times 10^6$

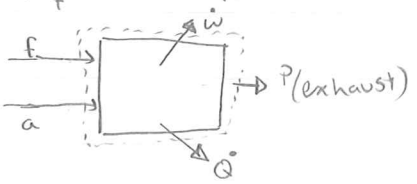
T	LHS
2400K	7.12×10^6

$\Rightarrow$ $T_{AFT} \cong 2400K$

Example: Energy balance on diesel engine

- A/F = 18
- $\dot{W} = 100$ kW
- $\dot{m}_f = 66.9$ g/s
- $T_f = T_{air} = 298$ K
- $T_p = 800$ K

diesel fuel
LHV = 43.2 MJ/kg
MW = 170 kg/kmol



a) find C_xH_y $\frac{y}{x} = 1.8$ $12x + y = 170$ $x = 12.32$ $y = 22.17$

b) find Stoich. Rxn

$$C_{12.32}H_{22.17} + a(O_2 + 3.76N_2) = 12.32CO_2 + \frac{22.17}{2}H_2O + 3.76aN_2$$

$a = 17.87$

c) find actual Rxn

$$C_{12.32}H_{22.17} + a(O_2 + 3.76N_2) \Rightarrow 12.32CO_2 + 11.09H_2O + bO_2 + 3.76aN_2$$

$$18 = \frac{a(4.76)(29)}{170} \Rightarrow a = 22.17$$

$$C_{12.32}H_{22.17} + 22.17(O_2 + 3.76N_2) \Rightarrow 12.32CO_2 + 11.09H_2O + 4.31O_2 + 83.36N_2$$

d) $\bar{h}^\circ_{f\,C_xH_y}$ $LHV = \sum_R n_i \bar{h}^\circ_f - \sum_P n_i \bar{h}^\circ_f$

$$(43.2 \times 10^3 \text{ kJ/kg} \times 170 \text{ kg/kmol}) = \bar{h}^\circ_{f\,C_xH_y} - 12.32\,\bar{h}^\circ_{f\,CO_2} - 11.09\,\bar{h}^\circ_{f\,H_2O}$$

$\bar{h}^\circ_{f\,C_xH_y} = -185{,}482$ kJ/kmol

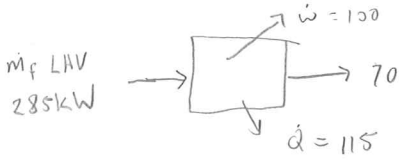
e) find $\dot{Q}$ $\bar{Q} - \bar{W} = \sum_P (\bar{h}^\circ_f + \Delta\bar{h})_i - \sum_R (\bar{h}^\circ_f + \Delta\bar{h})_i$

$\bar{Q} - \bar{W} = 12.32(-393{,}500 + 22{,}806) + 11.09 \ldots$

$\bar{Q} - \bar{W} = -5.541 \times 10^6$ kJ/kmol $\times \frac{1 \text{ kmol}}{170 \text{ kg}}$ $Q - W = -3.26 \times 10^4$ kJ/kg fuel

$\dot{Q} - \dot{W} = \dot{m}_f(Q - W) = .0066 \text{ kg/s}\,(-3.26 \times 10^4 \text{ kJ/kg}) = -215$ kW

$\dot{Q} = -215$ kW $+ 100$ kW $= \underline{-115 \text{ kW}}$



How to get an A

- bring review pages to class (from thermo 1)
- Homework due every day
- be able to sketch cycles for exam 1

Problems I copied: D13, D7

D14 after finding $W_{compressor}$

Test 2 avg 77 me 88
high 96
stdev 12.4

Copied problems for test 3:

Test 3 avg 74.4 me 99
high 100
stdev 18.9
low 35

Problems copied: D11

Test 3: D27