ROSE-HULMAN
INSTITUTE OF TECHNOLOGY

SOLUTIONS

Name

ME301 – Applications of Thermodynamics

Exam 2

Oct 26, 2023

Circle section:

01 [1 pm, Lui]	02 [2 pm, Lui]
03 [1 pm, Thom]	04 [2 pm, Thom]
05 [12 pm, Danesh]	05 [1 pm, Danesh]

Rules:

- Closed book/notes exam.
- Help sheets allowed. (Two 8-1/2 x 11" sheet of paper, one side, handwritten; may not contain worked out example problems)
- EES, Maple, Excel, and/or MATLAB are allowed on your laptop, but nothing may be prepared before the exam.
- Either open property tables (from your textbook) or open EES on your laptop.

Instructions:

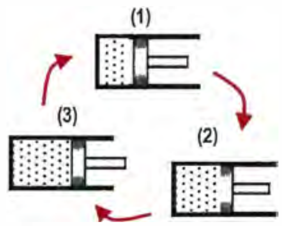
- Show all work for complete credit. *This includes clearly identifying all systems and transports for use with any conservation or accounting principle.*
- Work in symbols first, plugging in numbers and performing calculations last.

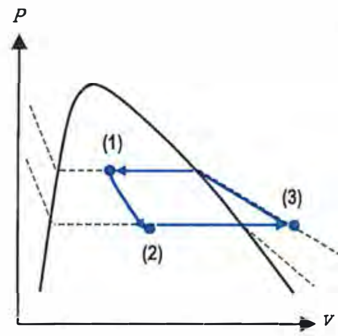
Problem 1	______/ 38
Problem 2	______/ 38
Problem 3	______/ 24
Total	______/100

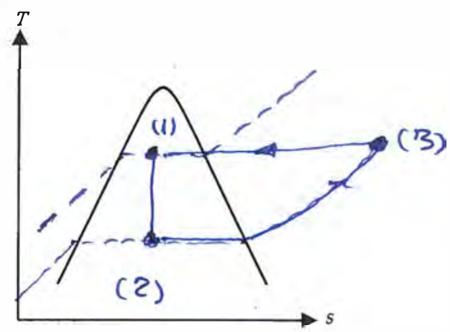
PROBLEM 1 [38 points]

A closed-system, periodic refrigeration cycle uses water as its working fluid. Some of the state information is given. (You do not have to fill in all table values.) The cycle can be modeled as consisting of the following three steps:

(1)→(2) Reversible, adiabatic expansion
(2)→(3) Constant-pressure heat addition
(3)→(1) Constant-temperature compression







State	T [°C]	P [kPa]	u [kJ/kg]	v [m³/kg]	x
1	81.3	50			0.70
2		6			
3				27.23	NA

(You do not have to fill in the whole table.)

	q_{in} [kJ/kg]	w_{in} [kJ/kg]
1→2		
2→3		
3→1	Do not calculate	396

(a) [6 pts] The *P-v* diagram for the cycle is shown. Draw the *T-s* diagram relative to the two-phase dome with properly labeled isobars.

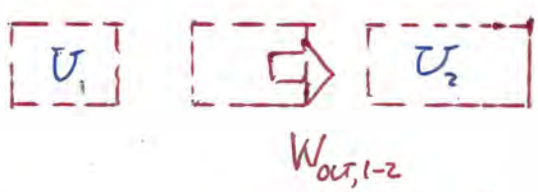
(b) [4 pts] Find the temperature T_1 in °C.

(c) [12 pts] Find the work per unit mass, $w_{1\to2}$, and indicate its direction (in or out of the water) for the process (1)→(2).

(d) [16 pts] Find the heat transfer per unit mass, $q_{2\to3}$, and the work per unit mass, $w_{2\to3}$ for the process (2)→(3).

(b) $T_1 = T_{SAT}(P = 50\ \text{kPa}) = 81.3\ °C$ ← ANS

(c) CoE, Finite time, closed system, no ke/pe



$U_2 - U_1 = \cancel{Q_{IN,12}}^{\,0} - W_{OUT,12}$

$m(u_2 - u_1) = -W_{OUT,12}$

$w_{OUT,1\to2} = \dfrac{W_{OUT,1-2}}{m} = \overset{\checkmark}{u_1} - \overset{?}{u_2}$

$u_1 = u(P = 50\ \text{kPa}, x_1 = 0.70)$

$= \underline{1840.3\ \text{kJ/kg}}$

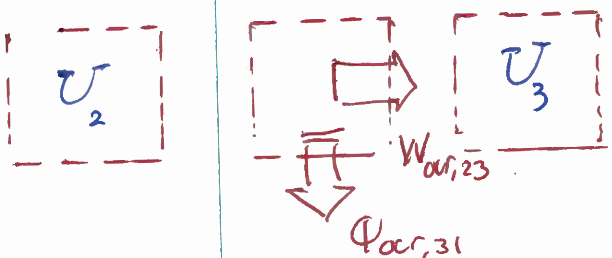
(1) → (2) Reversible, adiabatic
→ isentropic

$s_2 = s_1 = s(P_1, x_1) = \underline{5.642\ \text{kJ/kg}}$

$$u_2 = u(P_2, s_2) = \underline{1642.1 \text{ kJ/kg}}$$

$$w_{OUT,12} = (1840.3 - 1642.1)\frac{\text{kJ}}{\text{kg}} = 198.2 \frac{\text{kJ}}{\text{kg}} \longleftarrow \text{ANS}$$

(d) CoE, Finite time, closed, no ke/pe



$$U_3 - U_2 = Q_{IN,23} - W_{OUT,23}$$

$$m(u_3 - u_2) = \text{"} \quad \text{"}$$

$$u_3 - u_2 = \overset{?}{q_{IN,23}} - \overset{?}{w_{OUT,23}}$$

$$u_3 = u(v_3, T_3 = T_1) = \underline{2488.6 \text{ kJ/kg}}$$

$$w_{23} = \int_2^3 p\, dv = P(v_3 - v_2)$$

$$v_2 = v(P_2, s_2) = \underline{15.571 \text{ m}^3\text{/kg}}$$

$$= (6 \text{ kPa})(27.23 - 15.571 \frac{\text{m}^3}{\text{kg}})\left\langle \frac{\text{kJ}}{\cancel{\text{kPa}} \cdot \cancel{\text{m}^3}} \right\rangle$$

$$= 70.0 \frac{\text{kJ}}{\text{kg}} \longleftarrow \text{ANS}$$

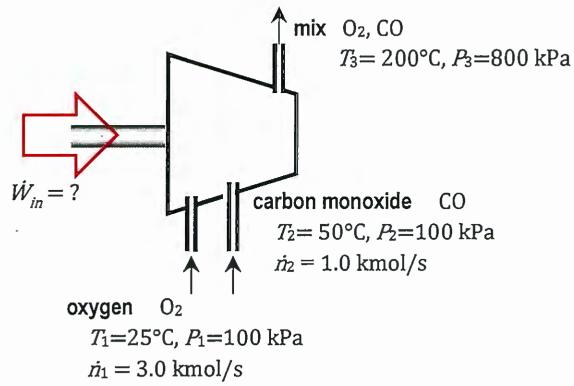
$$q_{23,IN} = u_3 - u_2 + w_{OUT,23}$$

$$= (2488.6 - 1642.1)\frac{\text{kJ}}{\text{kg}} + 70 \frac{\text{kJ}}{\text{kg}}$$

$$= 917 \frac{\text{kJ}}{\text{kg}} \longleftarrow \text{ANS}$$

PROBLEM 2 [38 points]

A $\dot{n}_1$=3.0 kmol/s of gaseous oxygen (T_1=25°C and P_1=100 kPa) and $\dot{n}_2$=1.0 kmol/s of carbon monoxide (T_2=50°C and P_2=100 kPa) enters compressor as two separate streams. Heat is transferred *out* of the compressor at a rate of 50 kW while the compressed product stream leaves at T_3=200°C and P_3=800 kPa.

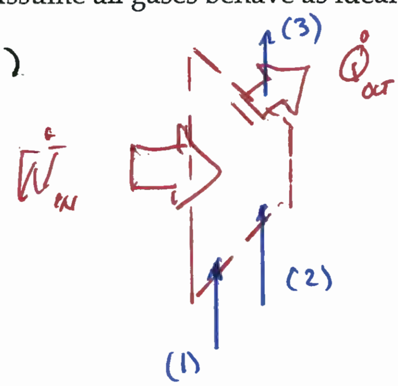


(a) [20 pts] Determine the power requirement to the compressor, in kW.

(b) [18 pts] Assuming a boundary temperature of T_b=120°C for the compressor, determine the rate of entropy generation in the compressor, in kW/K.

Assume all gases behave as ideal gases with variable specific heats. ✓

(a)



CoE $\frac{d}{dt}(\cancel{E_{sys}})^{0} = -\dot{Q}_{OUT} + \dot{W}_{IN} + \sum_{IN} \dot{n}\bar{h} - \sum_{OUT} \dot{n}\bar{h}$?

AoO$_2$

$\frac{d}{dt}(\cancel{n_{O_2}})^{0} = \sum \dot{n}_{O_2,IN} - \sum \dot{n}_{O_2,OUT}$

$= \dot{n}_1 - \dot{n}_{O_2,OUT}$

$\dot{n}_{O_2,3} = \dot{n}_1 = 3$ kmol/s

AoCO

$\frac{d}{dt}(\cancel{n_{CO}})^{0} = \sum \dot{n}_{CO,IN} - \sum \dot{n}_{N2,OUT}$

$0 = \dot{n}_2 - \dot{n}_{CO,3}$

$\dot{n}_{CO,3} = \dot{n}_2 = 1$ kmol/s

CoE becomes

$\dot{W}_{IN} = \dot{Q}_{OUT} + \dot{n}_{O_2,3}\bar{h}_{O_2,3} + \dot{n}_{CO,3}\bar{h}_{CO,3}$

$- \dot{n}_1 \bar{h}_{O_2,1} - \dot{n}_2 \bar{h}_{CO,2}$

$= \dot{Q}_{OUT} + \dot{n}_1(\bar{h}_{O_2,3} - \bar{h}_{O_2,1})$

$+ \dot{n}_2(\bar{h}_{CO,3} - \bar{h}_{CO,1})$

$= 50\text{ kW} + 3 \frac{\text{kmol}}{\text{s}}[13903.8 - 8682] \frac{\text{kJ}}{\text{kg}}$

$+ 1 \frac{\text{kmol}}{\text{s}}[13{,}797 - 9393.3] \frac{\text{kJ}}{\text{kg}}$

$\bar{h}_{O_2,1} = \bar{h}_{O_2}(T_1) = 8682. \frac{\text{kJ}}{\text{kg}}$

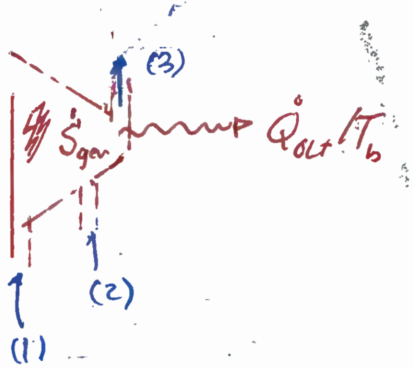
$\bar{h}_{CO,2} = \bar{h}_{CO}(T_2) = 9393.3$ "

$\bar{h}_{O_2,3} = \bar{h}_{O_2}(T_3) = 13{,}903.8$ "

$\bar{h}_{CO,3} = \bar{h}_{CO}(T_3) = 13{,}797$ "

$\dot{W}_{IN} = 20,120 \text{ W}$ ← ANS

(b)



AoS

$$\frac{d}{dt}\cancel{(S_{sys})}_{SS} = \sum \frac{\dot{Q}_{IN}}{T_b} + \sum_{IN} \dot{n}\bar{s} - \sum_{OUT} \dot{n}\bar{s} + \dot{S}_{gen}$$

$$0 = -\frac{\dot{Q}_{OUT}}{T_b} + \dot{n}_1 \bar{s}_{O2,1} + \dot{n}_2 \bar{s}_{CO,2} - \dot{n}_1 \bar{s}_{O2,3} - \dot{n}_2 \bar{s}_{CO,3} + \dot{S}_{gen}$$

$$\dot{S}_{gen} = \frac{\dot{Q}_{OUT}}{T_b} + \dot{n}_1(\bar{s}_3 - \bar{s}_1)_{O2} + \dot{n}_2(\bar{s}_3 - \bar{s}_2)_{CO}$$

$$O_2: \quad \bar{s}^{\circ}_{T3} - \bar{s}^{\circ}_{T1} - \bar{R}\ln\left(\frac{y_{O2,3}P_3}{P_1}\right) = [218.9 - 205.03]\frac{kJ}{kmol \cdot K} - 8.314\frac{kJ}{kmol \cdot K}\ln\left[\frac{(0.75)800}{100}\right]$$

$$= -1.30 \text{ kJ/kmol} \cdot \text{K}$$

$$CO: \quad \bar{s}^{\circ}_{T3} - \bar{s}^{\circ}_{T2} - \bar{R}\ln\left(\frac{y_{CO,3}P_3}{P_2}\right) = [211.1 - 199.9]\frac{kJ}{kg \cdot kmol} - 8.314\frac{kJ}{kmol \cdot K}\ln\left[\frac{(0.25)800}{100}\right]$$

$$= 5.44 \text{ kJ/kmol} \cdot \text{K}$$

$$\dot{S}_{gen} = \frac{50 \text{ kW}}{(120^{\circ}C + 273)K} + 3\frac{kmol}{s}\cdot[\quad] + 1\frac{kmol}{s}[\quad]$$

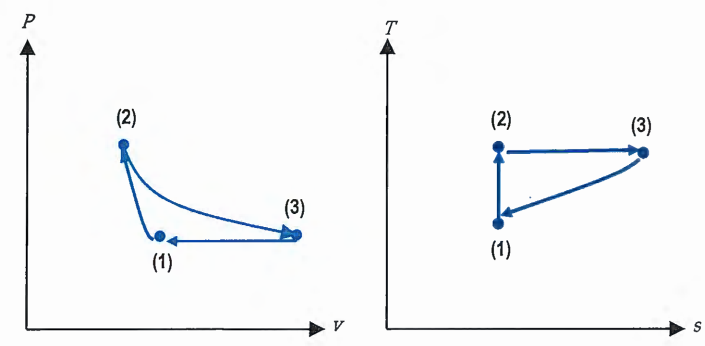
$$= 1.66 \frac{kW}{K}$$

$y_{O2,3} = \dot{n}_1/\dot{n}_3$
$= 0.75$

$y_{CO,3} = \dot{n}_2/\dot{n}_3$
$= 0.25$

PROBLEM 3 [24 points]

(a) [8 pts] Consider the closed-system, periodic cycle shown in the *P-v* and *T-s* diagrams below. The working fluid is a superheated vapor. All steps are internally reversible.



i. [2 pts] Which processes include heat transfer? Check all that apply.

- ☐ A. (1)→(2)
- ☑ B. (2)→(3)
- ☑ C. (3)→(1)

ii. [2 pts] How does the area contained *within* the curve (1)→(2)→(3)→(1) compare for the *P-v* and *T-s* diagrams?

- ○ A. $A_{P\text{-}v} < A_{T\text{-}s}$
- ◉ B. $A_{P\text{-}v} = A_{T\text{-}s}$
- ○ C. $A_{P\text{-}v} > A_{T\text{-}s}$
- ○ D. Cannot be determined

iii. [2 pts] How does the area under the curve (2)→(3) compare for the *P-v* and *T-s* diagrams?

- ○ A. $A_{P\text{-}v} < A_{T\text{-}s}$
- ○ B. $A_{P\text{-}v} = A_{T\text{-}s}$
- ○ C. $A_{P\text{-}v} < A_{T\text{-}s}$
- ◉ D. Cannot be determined

iv. [2 pts] The cycle is

- ◉ A. a heat engine (power cycle)
- ○ B. a refrigerator/heat pump
- ○ C. Cannot be determined

(b) [2 pts] What is the possible range of the efficiency for a heat engine?

- ◉ A. $0 < \eta < 1$
- ○ B. $0 < \eta < \infty$
- ○ C. $1 < \eta < \infty$

(c) [2 pts] When is it possible to use regeneration in a Brayton cycle?

- ◉ A. When the exit temperature of turbine is larger than the exit temperature of the compressor.
- ○ B. When the exit pressure of turbine is larger than the exit pressure of the compressor.
- ○ C. Both A and B
- ○ D. It is always possible.

(d) [2 pts] Increasing the boiler pressure of a Rankine cycle will generally

- ○ A. decrease cycle efficiency.
- ◉ B. increase cycle efficiency.
- ○ C. have no effect on cycle efficiency.

(e) [2 pts] For steady flow of a refrigerant through a throttling valve, which of the following properties *increase*? Check all that apply.

- ☐ A. h
- ☑ B. s
- ☐ C. a_f
- ☐ D. P

(f) [8 pts] For a mixture of ideal gases...

i.	True | False	$\sum_i y_i = 1$
ii.	True | False	$\sum_i mf_i = 1$
iii.	True | False	$\sum_i mf_i u_i = u_{mix}$
iv.	True | False	$\sum_i mf_i M_i = M_{mix}$