Name: Solution

ChBE 2130 Thermodynamics I

Fall 2015

Exam 3

Remember

- Write down relevant relationships needed to solve each problem
- Provide details, intermediate steps, and units
- Note any assumptions
- Show your work
- Where indicated, place your final answer on the ____________________
- **Submit your crib sheet with your exam.**

Problem	Possible Points	Score
1	20	
2	20	
3	20	
4	40	
Total		

1. Concept Questions **[20 pts: 5 points each,** no partial credit within sub-problem**]**

- For an ideal gas, simplify the equation, $V - T\left(\frac{\partial V}{\partial T}\right)_P$

  a. V
  b. R/P
  c. RT/P
  d. 0

for ideal gas $V = \frac{RT}{P}$ $\left(\frac{\partial V}{\partial T}\right)_P = \frac{R}{P}$

by substitution

$$\frac{RT}{P} - T\left(\frac{R}{P}\right) = 0$$

- Using the differential form of enthalpy as a basis, simplify $\left(\frac{\partial H}{\partial S}\right)_P$

  a. P
  b. T
  c. U
  d. 0

$$dH = TdS + VdP$$

constant $P \Rightarrow VdP = 0$

$$dH = TdS \qquad \left(\frac{\partial H}{\partial S}\right)_P = T$$

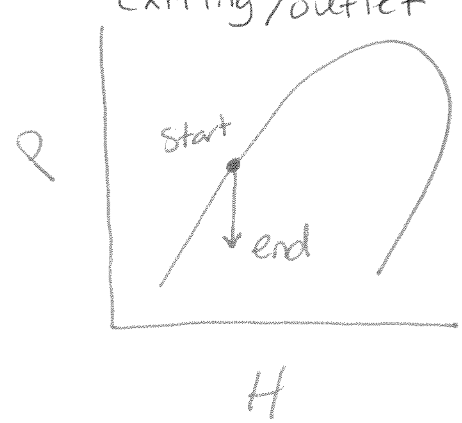
- A gas is flowing in an insulated duct of constant cross sectional area at stable conditions. Compared to the inlet conditions, the outlet will have

  a. Lower pressure and higher velocity
  b. Higher pressure and higher velocity
  c. Lower pressure and lower velocity
  d. Higher pressure and lower velocity

Gas → Compressible
Insulated → Adiabatic
Stable → Subsonic

- A saturated liquid at moderate temperature and pressure enter a throttle valve where the pressure is reduced by half. The ~~existing~~ exiting/outlet stream will consist of which of the following

  a. Subcooled liquid
  b. Saturated liquid
  c. Mixed phase – gas and liquid
  d. Saturated gas



Throttle ⇒ $\Delta H = 0$
Pressure is reduced

2. **[20 pts]** The behavior of a fluid is described by the following equation of state: $V = B + \left({}^{RT}/_{P}\right)$ where B is a constant. Develop a simplified expression for the residual enthalpy, H^R.

$$Z = \frac{PV}{RT} \quad \text{by substitution of } V = B + \left(\frac{RT}{P}\right)$$

$$Z = \frac{BP}{RT} + \frac{RTP}{RTP} = \frac{BP}{RT} + 1 \quad 6$$

$$Z = f(P,T)$$

$$\frac{H^R}{RT} = -\int_0^P T\left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} \quad 6$$

$$\left(\frac{\partial Z}{\partial T}\right)_P = -\frac{BP}{RT^2} \quad 4$$

$$\frac{H^R}{RT} = -\int_0^P T\left(-\frac{BP}{RT^2}\right)\frac{dP}{P} = \int_0^P \frac{B}{RT}\,dP \quad 2$$

$$\frac{H^R}{RT} = \frac{BP}{RT}\Big|_0^P$$

$$H^R = BP \quad 2$$

3. **[20 pts]** In terms of experimentally measurable properties, $\left(\frac{\partial T}{\partial V}\right)_S$ equals which of the following? Show your calculations and substitutions for full credit. Hint: Start with the cyclic relationship for $\left(\frac{\partial T}{\partial V}\right)_S$.

   a. $-\left(T/C_V\right)\left(\beta/\kappa\right)$
   b. $-\left(T/C_V\right)\left(1/\beta V\right)$
   c. $\left(C_P/T\right)\left(1/\beta V\right)$
   d. $\left(C_P/T\right)\left(\beta/\kappa\right)$

5 $\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial T}{\partial S}\right)_V\left(\frac{\partial S}{\partial V}\right)_T$

5 $-\left(\frac{\partial T}{\partial S}\right)_V = -\frac{T}{C_V}$ by definition

5 $\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$ by Maxwell EQ

5 $\left(\frac{\partial P}{\partial T}\right)_V = \beta/K$ by definition

$\left(\frac{\partial T}{\partial V}\right)_S = -\frac{T}{C_V}\left(\frac{\beta}{K}\right)$

8pts each

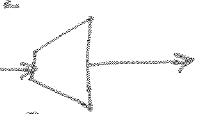
4. **[40 pts]** Steam enters a turbine at 2000 kPa and 500°C. The exhaust is at 20 kPa.

[16] a. If the turbine operates isentropically, what is the outlet phase and/or quality and the enthalpy?

$x = \frac{S^v - S}{S^v - S^l} = \frac{7.9094 - 7.4323}{7.9094 - 0.8321}$

$P_1 = 2000\,kPa$ $\quad P_2 = 20\,kPa$

$T_1 = 500°C$



$H_1 = 3467.3\ kJ/kg$

$S_1 = 7.4323\ kJ/kgK$

Phase/Quality Mixed $\quad x = 0.067$

$q = 0.933$

$H = xH^l + (1-x)H^v$

$H = 0.067(251.453) + (1-0.067)\,2609.9$

Outlet Enthalpy 2451.9 kJ/kg

OR $\quad H = 0.0674\,(251.453) + (1-0.0674)\,2609.9 = 2450.9$

[24] b. If work is produced at a rate of 2500 kW and the exhaust is saturated vapor, what is the outlet enthalpy, mass flow rate, and turbine efficiency? Note that a kW = kJ/s

20 kPa, sat. vapor $\rightarrow$ From Steam table

Outlet Enthalpy 2609.9 kJ/kg

$\dot{W} = \dot{m}\,\Delta H \qquad \dot{m} = \dot{W}/\Delta H$

$\frac{-2500\ kJ}{s} \Big| \frac{kg}{(2609.9 - 3467.3)\ kJ}$

Mass Flow Rate (in kg/s) 2.92 kg/s

$\eta = \frac{\Delta H}{\Delta H_{isen}} = \frac{2609.9 - 3467.3}{2451.9 - 3467.3}$

Efficiency 84.4%

OR

$\eta = \frac{\Delta H}{\Delta H_{isen}} = \frac{2609.9 - 3467.3}{2450.9 - 3467.3} = 84.36$

Table F.2. Superheated Steam, SI Units (Continued)

V = SPECIFIC VOLUME $cm^3\ g^{-1}$
U = SPECIFIC INTERNAL ENERGY $kJ\ kg^{-1}$
H = SPECIFIC ENTHALPY $kJ\ kg^{-1}$
S = SPECIFIC ENTROPY $kJ\ kg^{-1}\ K^{-1}$

TEMPERATURE: t °C
(TEMPERATURE: T kelvins)

P/kPa (t^{sat}/°C)		sat. liq.	sat. vap.	300 (573.15)	350 (623.15)	400 (673.15)	450 (723.15)	500 (773.15)	550 (823.15)	600 (873.15)	650 (923.15)
1	V	1.000	129200.	264500.	287580.	310660.	333730.	356810.	379880.	402960.	426040.
(6.98)	U	29.334	2385.2	2812.3	2889.9	2969.1	3049.9	3132.4	3216.7	3302.6	3390.3
	H	29.335	2514.4	3076.8	3177.5	3279.7	3383.6	3489.2	3596.5	3705.6	3816.4
	S	0.1060	8.9767	10.3450	10.5133	10.6711	10.8200	10.9612	11.0957	11.2243	11.3476
10	V	1.010	14670.	26440.	28750.	31060.	33370.	35670.	37980.	40290.	42600.
(45.83)	U	191.822	2438.0	2812.2	2889.8	2969.0	3049.8	3132.3	3216.6	3302.6	3390.3
	H	191.832	2584.8	3076.6	3177.3	3279.6	3383.5	3489.1	3596.5	3705.5	3816.3
	S	0.6493	8.1511	9.2820	9.4504	9.6083	9.7572	9.8984	10.0329	10.1616	10.2849
20	V	1.017	7649.8	13210.	14370.	15520.	16680.	17830.	18990.	20140.	21300.
(60.09)	U	251.432	2456.9	2812.0	2889.6	2968.9	3049.7	3132.3	3216.5	3302.5	3390.2
	H	251.453	2609.9	3076.4	3177.1	3279.4	3383.4	3489.0	3596.4	3705.4	3816.2
	S	0.8321	7.9094	8.9618	9.1303	9.2882	9.4372	9.5784	9.7130	9.8416	9.9650
30	V	1.022	5229.3	8810.8	9581.2	10350.	11120.	11890.	12660.	13430.	14190.
(69.12)	U	289.271	2468.6	2811.8	2889.5	2968.7	3049.6	3132.2	3216.5	3302.5	3390.2
	H	289.302	2625.4	3076.1	3176.9	3279.3	3383.3	3488.9	3596.3	3705.4	3816.2
	S	0.9441	7.7695	8.7744	8.9430	9.1010	9.2499	9.3912	9.5257	9.6544	9.7778
40	V	1.027	3993.4	6606.5	7184.6	7762.5	8340.1	8917.6	9494.9	10070.	10640.
(75.89)	U	317.609	2477.1	2811.6	2889.4	2968.6	3049.5	3132.1	3216.4	3302.4	3390.1
	H	317.650	2636.9	3075.9	3176.8	3279.1	3383.1	3488.8	3596.2	3705.3	3816.1
	S	1.0261	7.6709	8.6413	8.8100	8.9680	9.1170	9.2583	9.3929	9.5216	9.6450
50	V	1.030	3240.2	5283.9	5746.7	6209.1	6671.4	7133.5	7595.5	8057.4	8519.2
(81.35)	U	340.513	2484.0	2811.5	2889.2	2968.5	3049.4	3132.0	3216.3	3302.3	3390.1
	H	340.564	2646.0	3075.7	3176.6	3279.0	3383.0	3488.7	3596.1	3705.2	3816.0
	S	1.0912	7.5947	8.5380	8.7068	8.8649	9.0139	9.1552	9.2898	9.4185	9.5419
75	V	1.037	2216.9	3520.5	3829.4	4138.0	4446.4	4754.7	5062.8	5370.9	5678.9
(91.79)	U	384.374	2496.7	2811.0	2888.9	2968.2	3049.2	3131.8	3216.1	3302.2	3389.9
	H	384.451	2663.0	3075.1	3176.1	3278.6	3382.7	3488.4	3595.8	3705.0	3815.9
	S	1.2131	7.4570	8.3502	8.5191	8.6773	8.8265	8.9678	9.1025	9.2312	9.3546
100	V	1.043	1693.7	2638.7	2870.8	3102.5	3334.0	3565.3	3796.5	4027.7	4258.8
(99.63)	U	417.406	2506.1	2810.6	2888.6	2968.0	3049.0	3131.6	3216.0	3302.0	3389.8
	H	417.511	2675.4	3074.5	3175.6	3278.2	3382.4	3488.1	3595.6	3704.8	3815.7
	S	1.3027	7.3598	8.2166	8.3858	8.5442	8.6934	8.8348	8.9695	9.0982	9.2217

V = SPECIFIC VOLUME $cm^3\ g^{-1}$
U = SPECIFIC INTERNAL ENERGY $kJ\ kg^{-1}$
H = SPECIFIC ENTHALPY $kJ\ kg^{-1}$
S = SPECIFIC ENTROPY $kJ\ kg^{-1}\ K^{-1}$

Temperature °C

		Sat. liq.	Sat. vap.	400	425	450	475	500	550	600	650
1750 (205.72)	V	1.166	113.38	173.32	180.32	187.26	194.17	201.04	214.71	228.28	241.80
	U	876.234	2595.7	2949.3	2991.3	3033.4	3075.7	3118.2	3204.3	3291.8	3380.8
	H	878.274	2794.1	3252.7	3306.9	3361.1	3415.5	3470.0	3580.0	3691.3	3803.9
	S	2.3846	6.3853	7.1955	7.2746	7.3509	7.4248	7.4965	7.6344	7.7656	7.8910
1800 (207.11)	V	1.168	110.32	168.39	175.20	181.97	188.69	195.38	208.68	221.89	235.03
	U	882.472	2596.3	2948.8	2990.8	3032.9	3075.2	3117.8	3203.9	3291.5	3380.5
	H	884.574	2794.8	3251.9	3306.1	3360.4	3414.9	3469.5	3579.5	3690.9	3803.6
	S	2.3976	6.3751	7.1816	7.2608	7.3372	7.4112	7.4830	7.6209	7.7522	7.8777
1850 (208.47)	V	1.170	107.41	163.73	170.37	176.96	183.50	190.02	202.97	215.84	228.64
	U	888.585	2596.8	2948.2	2990.3	3032.4	3074.8	3117.4	3203.6	3291.1	3380.2
	H	890.750	2795.5	3251.1	3305.4	3359.8	3414.3	3468.9	3579.1	3690.4	3803.2
	S	2.4103	6.3651	7.1681	7.2474	7.3239	7.3980	7.4698	7.6079	7.7392	7.8648
1900 (209.80)	V	1.172	104.65	159.30	165.78	172.21	178.59	184.94	197.57	210.11	222.58
	U	894.580	2597.3	2947.6	2989.7	3031.9	3074.3	3117.0	3203.2	3290.8	3380.0
	H	896.807	2796.1	3250.3	3304.7	3359.1	3413.7	3468.4	3578.6	3690.0	3802.8
	S	2.4228	6.3554	7.1550	7.2344	7.3109	7.3851	7.4570	7.5951	7.7265	7.8522
1950 (211.10)	V	1.174	102.031	155.11	161.43	167.70	173.93	180.13	192.44	204.67	216.83
	U	900.461	2597.7	2947.0	2989.2	3031.5	3073.9	3116.6	3202.9	3290.5	3379.7
	H	902.752	2796.7	3249.5	3304.0	3358.5	3413.1	3467.8	3578.1	3689.6	3802.5
	S	2.4349	6.3459	7.1421	7.2216	7.2983	7.3725	7.4445	7.5827	7.7142	7.8399
2000 (212.37)	V	1.177	99.536	151.13	157.30	163.42	169.51	175.55	187.57	199.50	211.36
	U	906.236	2598.2	2946.4	2988.7	3031.0	3073.5	3116.2	3202.5	3290.2	3379.4
	H	908.589	2797.2	3248.7	3303.3	3357.8	3412.5	3467.3	3577.6	3689.2	3802.1
	S	2.4469	6.3366	7.1296	7.2092	7.2859	7.3602	7.4323	7.5706	7.7022	7.8279
2100 (214.85)	V	1.181	94.890	143.73	149.63	155.48	161.28	167.06	178.53	189.91	201.22
	U	917.479	2598.9	2945.3	2987.6	3030.0	3072.6	3115.3	3201.8	3289.6	3378.9
	H	919.959	2798.2	3247.1	3301.8	3356.5	3411.3	3466.2	3576.7	3688.4	3801.4
	S	2.4700	6.3187	7.1053	7.1851	7.2621	7.3365	7.4087	7.5472	7.6789	7.8048
2200 (217.24)	V	1.185	90.652	137.00	142.65	148.25	153.81	159.34	170.30	181.19	192.00
	U	928.346	2599.6	2944.1	2986.6	3029.1	3071.7	3114.5	3201.1	3289.0	3378.3
	H	930.953	2799.1	3245.5	3300.4	3355.2	3410.1	3465.1	3575.7	3687.6	3800.7
	S	2.4922	6.3015	7.0821	7.1621	7.2393	7.3139	7.3862	7.5249	7.6568	7.7827
2300 (219.55)	V	1.189	86.769	130.85	136.28	141.65	146.99	152.28	162.80	173.22	183.58
	U	938.866	2600.2	2942.9	2985.5	3028.1	3070.8	3113.7	3200.4	3288.3	3377.8
	H	941.601	2799.8	3243.9	3299.0	3353.9	3408.9	3464.0	3574.8	3686.7	3800.0
	S	2.5136	6.2849	7.0598	7.1401	7.2174	7.2922	7.3646	7.5035	7.6355	7.7616