Massachusetts Institute of Technology
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16.003/16.003 Unified Engineering III, IV
Spring 2009

Problem Set 6

Name: ________________________

Due Date: 3/20/2009

	Time Spent (min)
T12	
T13-14	
S1	
Study Time	

Announcements:

Unified Engineering Spring 2009
Thermodynamics & Propulsion Z. S. Spakovszky

(Add a short summary of the concepts you are using to solve the problem)

Problem T12

Consider the following Rankine cycles. Steam at 20 bar, 360°C is expanded in a steam turbine to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler.

a) Assuming ideal processes, sketch the cycle in a T-s diagram and find the net work and the cycle efficiency per kg of steam.

b) If the turbine and the pump each have 80% efficiency, find the percentage reduction in the net work and cycle efficiency. Sketch the non-ideal cycle in the same T-s diagram.

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(Add a short summary of the concepts you are using to solve the problem)

Problem T13 – T14

One method of producing liquid nitrogen is to use the system shown below. Nitrogen gas at a pressure of 100 bar and a temperature of 300 K flows at a rate of 10 m^3/min (measured at 1 bar) through the heat exchanger, thereby decreasing in temperature. As it flows through the Joule-Thomson valve, its pressure is reduced from 100 bar to 1 bar and in the process some liquid is formed. The gas which is not liquefied, but has a reduced temperature, flows out through the counter-flow heat exchanger. The temperature of this discharge stream is 297 K. Assume that the heat exchange is externally adiabatic.

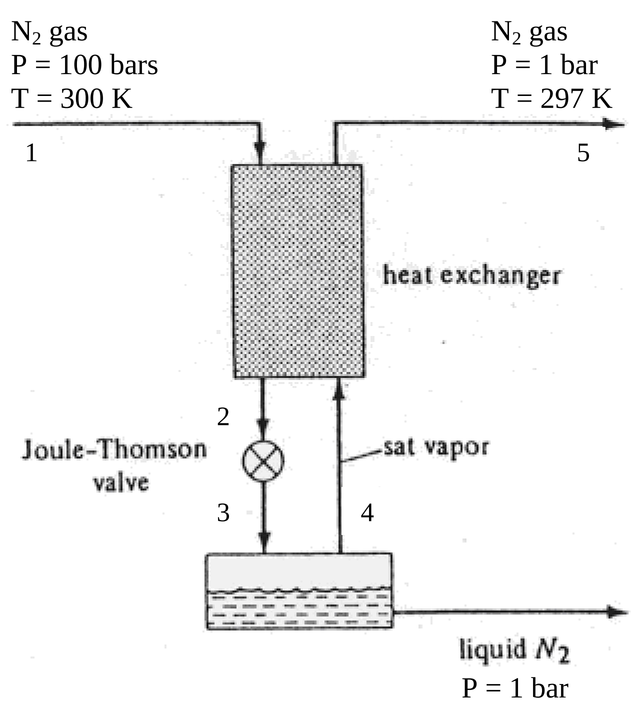
a) Sketch the process in a T-s diagram and label all states.

b) Find the mass flow into the heat exchanger.

c) Determine the heat transferred in the heat exchanger.

d) Determine the rate at which liquid nitrogen is delivered by this system.

e) Sketch the temperature difference in the heat exchanger versus the temperature of the low-pressure stream. Is the heat transfer process in the heat exchanger reversible? Why or why not? (No calculation is needed here, an explanation in a few sentences is expected)



Thermodynamic Properties of Nitrogen

TABLE B.6 SI *Thermodynamic Properties of Nitrogen*

TABLE B.6.1 SI *Saturated Nitrogen*

Temp.	Press.	Specific Volume, m^3/kg			Internal Energy, kJ/kg		
K T	kPa P	Sat. Liquid v_f	Evap. v_{fg}	Sat. Vapor v_g	Sat. Liquid u_f	Evap. u_{fg}	Sat. Vapor u_g
63.1	12.5	0.001150	1.48074	1.48189	-150.92	196.86	45.94
65	17.4	0.001160	1.09231	1.09347	-147.19	194.37	47.17
70	38.6	0.001191	0.52513	0.52632	-137.13	187.54	50.40
75	76.1	0.001223	0.28052	0.28174	-127.04	180.47	53.43
77.3	101.3	0.001240	0.21515	0.21639	-122.27	177.04	54.76
80	137.0	0.001259	0.16249	0.16375	-116.86	173.06	56.20
85	229.1	0.001299	0.10018	0.10148	-106.55	165.20	58.65
90	360.8	0.001343	0.06477	0.06611	-96.06	156.76	60.70
95	541.1	0.001393	0.04337	0.04476	-85.35	147.60	62.25
100	779.2	0.001452	0.02975	0.03120	-74.33	137.50	63.17
105	1084.6	0.001522	0.02066	0.02218	-62.89	126.18	63.29
110	1467.6	0.001610	0.01434	0.01595	-50.81	113.11	62.31
115	1939.3	0.001729	0.00971	0.01144	-37.66	97.36	59.70
120	2513.0	0.001915	0.00608	0.00799	-22.42	76.63	54.21
125	3208.0	0.002355	0.00254	0.00490	-0.83	40.73	39.90
126.2	3397.8	0.003194	0	0.00319	18.94	0	18.94

TABLE B.6.2 SI *Superheated Nitrogen*

Temp. K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K
	100 kPa (77.24)			200 kPa (83.62)			500 kPa (93.98)		
Sat.	0.21903	76.61	5.4059	0.11520	81.05	5.2673	0.04834	86.15	5.0802
100	0.29103	101.94	5.6944	0.14252	100.24	5.4775	0.05306	94.46	5.1660
120	0.35208	123.15	5.8878	0.17397	121.93	5.6753	0.06701	118.12	5.3821
140	0.41253	144.20	6.0501	0.20476	143.28	5.8399	0.08007	140.44	5.5541
160	0.47263	165.17	6.1901	0.23519	164.44	5.9812	0.09272	162.22	5.6996
180	0.53254	186.09	6.3132	0.26542	185.49	6.1052	0.10515	183.70	5.8261
200	0.59231	206.97	6.4232	0.29551	206.48	6.2157	0.11744	205.00	5.9383
220	0.65199	227.83	6.5227	0.32552	227.41	6.3155	0.12964	226.18	6.0392
240	0.71161	248.67	6.6133	0.35546	248.32	6.4064	0.14177	247.27	6.1310
260	0.77118	269.51	6.6967	0.38535	269.21	6.4900	0.15385	268.31	6.2152
280	0.83072	290.33	6.7739	0.41520	290.08	6.5674	0.16590	289.31	6.2930

TABLE B.6.1 SI (Continued) *Saturated Nitrogen*

Temp.	Press.	Enthalpy, kJ/kg			Entropy, kJ/kg K		
K T	kPa P	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
63.1	12.5	-150.91	215.39	64.48	2.4234	3.4109	5.8343
65	17.4	-147.17	213.38	66.21	2.4816	3.2828	5.7645
70	38.6	-137.09	207.79	70.70	2.6307	2.9684	5.5991
75	76.1	-126.95	201.82	74.87	2.7700	2.6909	5.4609
77.3	101.3	-122.15	198.84	76.69	2.8326	2.5707	5.4033
80	137.0	-116.69	195.32	78.63	2.9014	2.4415	5.3429
85	229.1	-106.25	188.15	81.90	3.0266	2.2135	5.2401
90	360.8	-95.58	180.13	84.55	3.1466	2.0015	5.1480
95	541.1	-84.59	171.07	86.47	3.2627	1.8007	5.0634
100	779.2	-73.20	160.68	87.48	3.3761	1.6068	4.9829
105	1084.6	-61.24	148.59	87.35	3.4883	1.4151	4.9034
110	1467.6	-48.45	134.15	85.71	3.6017	1.2196	4.8213
115	1939.3	-34.31	116.19	81.88	3.7204	1.0104	4.7307
120	2513.0	-17.61	91.91	74.30	3.8536	0.7659	4.6195
125	3208.0	6.73	48.88	55.60	4.0399	0.3910	4.4309
126.2	3397.8	29.79	0	29.79	4.2193	0	4.2193

TABLE B.6.2 SI (Continued) *Superheated Nitrogen*

Temp. K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	100 kPa (77.24)			200 kPa (83.62)			500 kPa (93.98)		
300	0.89023	311.16	6.8457	0.44503	310.94	6.6393	0.17792	310.28	6.3653
350	1.03891	363.24	7.0063	0.51952	363.09	6.8001	0.20788	362.63	6.5267
400	1.18752	415.41	7.1456	0.59392	415.31	6.9396	0.23777	414.99	6.6666
450	1.33607	467.77	7.2690	0.66827	467.70	7.0630	0.26759	467.49	6.7902
500	1.48458	520.41	7.3799	0.74258	520.37	7.1740	0.29739	520.24	6.9014
600	1.78154	626.94	7.5741	0.89114	626.94	7.3682	0.35691	626.93	7.0959
700	2.07845	735.58	7.7415	1.03965	735.61	7.5357	0.41637	735.68	7.2635
800	2.37532	846.60	7.8897	1.18812	846.64	7.6839	0.47581	846.78	7.4118
900	2.67217	960.01	8.0232	1.33657	960.07	7.8175	0.53522	960.24	7.5454
1000	2.96900	1075.68	8.1451	1.48501	1075.75	7.9393	0.59462	1075.96	7.6673

TABLE B.6.2 SI (Continued) *Superheated Nitrogen*

Temp. K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	600 kPa (96.37)			800 kPa (100.38)			1000 kPa (103.73)		
Sat.	0.04046	86.85	5.0411	0.03038	87.52	4.9768	0.02416	87.51	4.9237
120	0.05510	116.79	5.3204	0.04017	114.02	5.2191	0.03117	111.08	5.1357
140	0.06620	139.47	5.4953	0.04886	137.50	5.4002	0.03845	135.47	5.3239
160	0.07689	161.47	5.6422	0.05710	159.95	5.5501	0.04522	158.42	5.4772
180	0.08734	183.10	5.7696	0.06509	181.89	5.6793	0.05173	180.67	5.6082
200	0.09766	204.50	5.8823	0.07293	203.51	5.7933	0.05809	202.52	5.7234
220	0.10788	225.76	5.9837	0.08067	224.94	5.8954	0.06436	224.11	5.8263
240	0.11803	246.92	6.0757	0.08835	246.23	5.9880	0.07055	245.53	5.9194
260	0.12813	268.01	6.1601	0.09599	267.42	6.0728	0.07670	266.83	6.0047
280	0.13820	289.05	6.2381	0.10358	288.54	6.1511	0.08281	288.04	6.0833
300	0.14824	310.06	6.3105	0.11115	309.62	6.2238	0.08889	309.18	6.1562
350	0.17326	362.48	6.4722	0.12998	362.17	6.3858	0.10401	361.87	6.3187
400	0.19819	414.89	6.6121	0.14873	414.68	6.5260	0.11905	414.47	6.4591
450	0.22308	467.42	6.7359	0.16743	467.28	6.6500	0.13404	467.15	6.5832
500	0.24792	520.20	6.8471	0.18609	520.12	6.7613	0.14899	520.04	6.6947
600	0.29755	626.93	7.0416	0.22335	626.93	6.9560	0.17883	626.92	6.8895
700	0.34712	735.70	7.2093	0.26056	735.76	7.1237	0.20862	735.81	7.0573
800	0.39666	846.82	7.3576	0.29773	846.91	7.2721	0.23837	847.00	7.2057
900	0.44618	960.30	7.4912	0.33488	960.42	7.4058	0.26810	960.54	7.3394
1000	0.49568	1076.02	7.6131	0.37202	1076.16	7.5277	0.29782	1076.30	7.4614
	1500 kPa (110.38)			2000 kPa (115.58)			3000 kPa (123.61)		
Sat.	0.01555	85.51	4.8148	0.01100	81.25	4.7193	0.00582	63.47	4.5032
120	0.01899	102.75	4.9650	0.01260	92.10	4.8116	—	—	—
140	0.02452	130.15	5.1767	0.01752	124.40	5.0618	0.01038	111.13	4.8706
160	0.02937	154.50	5.3394	0.02144	150.43	5.2358	0.01350	141.85	5.0763
180	0.03393	177.60	5.4755	0.02503	174.48	5.3775	0.01614	168.09	5.2310
200	0.03832	200.03	5.5937	0.02844	197.53	5.4989	0.01857	192.49	5.3596
220	0.04260	222.05	5.6987	0.03174	219.99	5.6060	0.02088	215.88	5.4711
240	0.04682	243.80	5.7933	0.03496	242.08	5.7021	0.02312	238.66	5.5702
260	0.05099	265.36	5.8796	0.03814	263.90	5.7894	0.02531	261.02	5.6597
280	0.05512	286.78	5.9590	0.04128	285.53	5.8696	0.02746	283.09	5.7414
300	0.05922	308.10	6.0325	0.04440	307.03	5.9438	0.02958	304.94	5.8168
350	0.06940	361.13	6.1960	0.05209	360.39	6.1083	0.03480	358.96	5.9834
400	0.07949	413.96	6.3371	0.05971	413.47	6.2500	0.03993	412.50	6.1264
450	0.08953	466.82	6.4616	0.06727	466.49	6.3750	0.04502	465.87	6.2521
500	0.09953	519.84	6.5733	0.07480	519.65	6.4870	0.05008	519.29	6.3647
600	0.11948	626.92	6.7685	0.08980	626.93	6.6825	0.06013	626.95	6.5609
700	0.13937	735.94	6.9365	0.10474	736.07	6.8507	0.07012	736.35	6.7295
800	0.15923	847.22	7.0851	0.11965	847.45	6.9994	0.08008	847.92	6.8785
900	0.17906	960.83	7.2189	0.13454	961.13	7.1333	0.09003	961.73	7.0125
1000	0.19889	1076.65	7.3409	0.14942	1077.01	7.2553	0.09996	1077.72	7.1347

TABLE B.6.2 SI *Superheated Nitrogen*

Temp. K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K
	6000 kPa			8000 kPa			10000 kPa		
140	0.002941	47.44	4.2926	0.002224	27.78	4.1167	0.002003	20.87	4.0373
160	0.005556	112.16	4.7292	0.003748	91.80	4.5453	0.002908	76.52	4.4088
180	0.007309	148.02	4.9411	0.005193	134.69	4.7988	0.004021	122.65	4.6813
200	0.008771	177.29	5.0955	0.006387	167.47	4.9717	0.005014	158.35	4.8697
220	0.010095	203.77	5.2217	0.007449	196.07	5.1082	0.005902	188.88	5.0153
240	0.011337	228.73	5.3303	0.008433	222.48	5.2231	0.006721	216.64	5.1362
260	0.012526	252.73	5.4264	0.009367	247.55	5.3235	0.007495	242.72	5.2406
280	0.013678	276.09	5.5130	0.010264	271.74	5.4131	0.008235	267.69	5.3331
300	0.014803	298.99	5.5920	0.011135	295.32	5.4945	0.008952	291.90	5.4167
350	0.017532	354.95	5.7646	0.013236	352.51	5.6709	0.010670	350.26	5.5967
400	0.020187	409.83	5.9111	0.015264	408.24	5.8197	0.012320	406.79	5.7477
450	0.022794	464.19	6.0392	0.017248	463.22	5.9492	0.013927	462.36	5.8786
500	0.025370	518.37	6.1534	0.019202	517.88	6.0644	0.015507	517.48	5.9948
600	0.030463	627.12	6.3516	0.023053	627.32	6.2639	0.018611	627.58	6.1955
700	0.035506	737.27	6.5214	0.026856	737.94	6.4344	0.021669	738.65	6.3667
800	0.040519	849.37	6.6710	0.030631	850.38	6.5845	0.024700	851.43	6.5172
900	0.045514	963.59	6.8055	0.034388	964.86	6.7194	0.027714	966.15	6.6523
1000	0.050495	1079.88	6.9281	0.038132	1081.35	6.8421	0.030715	1082.84	6.7753
	15000 kPa			20000 kPa			50000 kPa		
140	0.001770	14.81	3.9273	0.001655	13.75	3.8587	0.001391	28.05	3.6405
160	0.002183	59.14	4.2232	0.001929	53.63	4.1250	0.001497	61.62	3.8647
180	0.002749	102.34	4.4778	0.002281	93.02	4.3570	0.001612	94.31	4.0573
200	0.003365	140.60	4.6796	0.002687	130.17	4.5529	0.001736	126.15	4.2250
220	0.003964	174.10	4.8394	0.003108	164.26	4.7154	0.001867	157.12	4.3726
240	0.004531	204.33	4.9710	0.003525	195.59	4.8518	0.002003	187.24	4.5037
260	0.005071	232.41	5.0834	0.003930	224.82	4.9689	0.002143	216.53	4.6209
280	0.005589	259.01	5.1820	0.004323	252.50	5.0714	0.002285	245.02	4.7266
300	0.006088	284.56	5.2702	0.004704	279.01	5.1629	0.002428	272.78	4.8223
350	0.007280	345.47	5.4581	0.005617	341.86	5.3568	0.002786	339.44	5.0280
400	0.008416	403.79	5.6139	0.006487	401.65	5.5166	0.003138	403.08	5.1980
450	0.009517	460.71	5.7480	0.007329	459.70	5.6534	0.003484	464.64	5.3431
500	0.010593	516.88	5.8664	0.008149	516.78	5.7737	0.003823	524.82	5.4699
600	0.012697	628.50	6.0699	0.009748	629.76	5.9797	0.004484	642.94	5.6853
700	0.014759	740.63	6.2427	0.011310	742.85	6.1540	0.005129	760.04	5.8658
800	0.016797	854.18	6.3943	0.012849	857.11	6.3065	0.005762	877.47	6.0226
900	0.018818	969.50	6.5301	0.014374	972.98	6.4430	0.006385	995.87	6.1621
1000	0.020828	1086.64	6.6535	0.015887	1090.55	6.5668	0.007001	1115.51	6.2881

Signals and Systems 1:

Please do problems 1.21, 1.22, 1.25, and 1.26 from Oppenheim and Willsky.