2.451J and 22.571J

GENERAL THERMODYNAMICS

Problem Set 1 **Due: September 20, 1990**

1. Which of the following systems are the same ?

(a) An amount of 1 kg of water in a cylinder with an adjustable piston is in a gravitational field. The volume of the cylinder varies from 0 to 1 m^3, and the field from 0 to 1 g.

(b) An amount of 1 kg of water is confined in a vessel of volume 1 m^3. The vessel is in a gravitational field of 1 g.

(c) An amount of 1 kg of water in a cylinder with an adjustable piston as in (a) is in a spacecraft orbiting the earth.

(d) An amount of 1 kg of water in a cylinder with an adjustable piston as in (a) is in a spacecraft commuting between the surface of the earth and an orbit.

(e) An amount of 1 kg of water in a cylinder with an adjustable piston as in (a) is in a spacecraft commuting between the surface of Jupiter and an orbit.

(f) An amount of water between 0 and 1 kg in a cylinder with an adjustable piston as in (a) is in a gravitational field that varies from 0 to 1 g.

2. At a given point in time, system A consists of 10 water molecules, H_20, in a vessel, system B consists of 10 hydrogen molecules, H_2, and 10 oxygen atoms, O, in a vessel identical to that of A, and system C consists of 100 water molecules in a vessel identical to that of A.

Are systems A, B and C completely defined ? If yes, are they identical ? If no, define them such that systems A, B and C are identical.

3. Consider a system consisting of a water molecule in a rigid container.Which of the following are properties of the system?

(a) The position of the molecule.

(b) The speed of the molecule.

(c) The path of the molecule between two points in time.

(d) The interaction with another system needed to accelerate the molecule from a lower to a higher speed.

4. Problem 2.10

5. What is the difference between a property and a state ?

6. Problem 3.6

7. Problem 3.17

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GENERAL THERMODYNAMICS

Problem Set 2 **Due: September 27, 1990**

1. In the tutorial session on September 18, the two following issues remained unresolved:

   (a) Are friction forces internal or external ? Think about your answer (s) carefully.

   (b) The constituents of a system are billiard balls identical in every respect except that each ball has either a stripe or uniform colour. Is each kind of ball a different constituent ? Justify your answer(s).

2. Problem 3.26

3. Problem 4.6

4. Problem 4.9

5. Problem 5.4

6. Problem 3.27. It will not be graded, but you are encouraged to work it and hand it in for your own edification.

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GENERAL THERMODYNAMICS

Problem Set 3 **Due: October 4, 1990**

1. Problem 3.24

2. Problem 6.1

3. A well-insulated water tank in state 1 is filled with hot water on top and cold water at the bottom. In state 2, the water in the tank is in a stable equilibrium state with the same energy as in state 1. In all states considered in this problem, the volume of the tank and the amount of water in it are the same.

   (a) What kind of state is state 1 ?

   (b) If the water in the tank in state 2 is connected with a reservoir R through cyclic machinery, energy can be transferred to a weight in a reversible process in the amount of 240 MJ . What are the adiabatic availability and the available energy with respect to reservoir R of state 2 ?

   (c) If the tank in state 1 is connected to reservoir R through cyclic machinery, energy can be transferred to a weight in a reversible process in the amount of 300 MJ . What is the available energy with respect to reservoir R of the tank in state 1 ?

   (d) State 3, a stable equilibrium state, is reached by a reversible process from state 1. If the tank in state 3 is connected to reservoir R through cyclic machinery, energy can be transferred to a weight in a reversible process in the amount of 120 MJ. What is the adiabatic availability of state 1 ?

   (e) The price for 1 MJ of energy that can be transferred to a weight is 10 cents. How much money is lost if the tank is allowed to change from state 1 to state 2 ?

4. Problem 6.7

5. Problem 7.1

6. Problem 7.3

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GENERAL THERMODYNAMICS

Problem Set 4 **Due: October 11, 1990**

1. Problem 8.3
2. Problem 8.4
3. Problem 9.2
4. Problem 9.3
5. Problem 9.4

Elias!

- Could you please prepare Problem Set 5?
- Farid will give you the solution to Problem Set 4 for review.
- I will be back on Monday, October 15, 1990.

Sincerely,

[signature]

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GENERAL THERMODYNAMICS

Problem Set 5 Due: October 18, 1990

1. Problem 11.1

2. Problem 11.4

3. Problem 12.2

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General Thermodynamics

Midterm Examination I

October 18, 1990

Problem 1 (30/100)

System A consists of only one constituent, and has only volume V as a parameter. In stable equilibrium state A_1, the system has

Energy	Volume	Amount of constituent
$E_1 = 2.4 \times 10^5$ J	$V_1 = 2.4 \times 10^{-6}$ m^3	$n_1 = 24$ mol

Around state A_1, the fundamental relation can be accurately represented by the expression

$$S = 100(E\,V\,n)^{1/3}$$

where S is in J/K for E in J, V in m^3, and n in mol.

(5/100) a. Find the entropy S_1 of A in state A_1.

(15/100) b. Find the temperature T_1, the pressure p_1, and the chemical potential μ_1 of A in state A_1.

(5/100) c. Write a relation between small changes in energy, entropy, volume, and amount of the constituent from one to another stable equilibrium state.

(5/100) d. Consider a stable equilibrium state A_2 that has energy E_2, entropy $S_2 = 240 + 10$ J/K, volume $V_2 = 2.4 \times 10^{-6} + 1.2 \times 10^{-7}$ m^3, and amount of the constituent $n_2 = 24 + 0.5$ mol. Estimate the difference in energies $E_2 - E_1$ using the result in part (c).

Problem 2 (35/100)

Consider two large, rigid tanks A and B. Tank A is filled with $m_v = 5000$ kg of a vapor at 700° C, and tank B with $m_g = 10{,}000$ kg of a gas at 400° C. For the stable equilibrium states of interest in this problem, the energy and entropy of either the vapor or the gas can be written as $E = mc\,(T - T_o)$ and $S = mc\ln(T/T_o)$, where for the vapor $c_v = 1.8$ kJ/kg K and for the gas $c_g = 1.2$ kJ/kg K, and T_o is a constant expressed in kelvin.

Energy can be transferred to a weight from the composite of the rigid tanks by using a thermoelectric generator to power a motor.

(15/100) a. What is the largest amount of energy that can be transferred to the weight in a weight process for the composite of A and B ?

(10/100) b. If in an irreversible weight process for the composite of A and B, the two systems A and B end in mutual stable equilibrium, and the weight receives half as much energy as in the weight process in part (a), how much entropy is generated by irreversibility in both A and B ?

(10/100) c. Considering your result in part (b), can you tell what fraction of the entropy generated by irreversibility is generated in A and what fraction in B ? State your answer in a few lines.

Problem 3 (35/100)

Four states A_0, A_1, A_2, A_3 of system A correspond to the same values of amounts of constituents and parameters. In addition, all states of reservoir R correspond to fixed values of amounts of constituents and parameters.

In state A_0 system A has energy $E_0 = 0$, and is in mutual stable equilibrium with R. In addition, measurements yield the following results.

(α) $\left[W_{10}^{AR\rightarrow}\right]_{rev} = 70$ kJ

(β) $\left[W_{20}^{AR\rightarrow}\right]_{rev} = \left[W_{20}^{A\rightarrow}\right]_{rev} = 40$ kJ

(γ) $\left[W_{30}^{AR\rightarrow}\right]_{rev} = 20$ kJ

(δ) $\left[W_{12}^{A\rightarrow}\right]_{irr} = 0$ and $(S_{12})_{irr} = 0.1$ kJ/K

(ϵ) $\left[W_{13}^{A\rightarrow}\right]_{irr} = 0$

(15/100) (a) What are the values of the energies E_1, E_2, and E_3 of system A ?

(10/100) (b) What is the temperature of the reservoir T_R ?

(10/100) (c) How much entropy is generated by irreversibility in the course of the irreversible weight process from A_1 to A_3 ?

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Solution, Midterm Examination, 10/18/90

Problem 1

a. $S_1 = 100\left(2.4\times10^5 \times 2.4\times10^{-6} \times 24\right)^{1/3} = 240 \text{ J/K}.$

b. $E = \left(\frac{S}{100}\right)^3 \frac{1}{Vn}$

$$\left(\frac{\partial E}{\partial S}\right)_{V,n} = \frac{3S^2}{10^6}\,\frac{1}{Vn} \qquad T_1 = \frac{3\times 240^2}{10^6}\,\frac{1}{2.4\times10^{-6}\times 24}$$

$$= 3000 \text{ K}$$

$$\left(\frac{\partial E}{\partial V}\right)_{S,n} = -\left(\frac{S}{100}\right)^3 \frac{1}{V^2 n} \qquad p_1 = \frac{(2.4)^3}{(2.4\times10^{-6})^2\times 24} =$$

$$= 10^{11} \frac{N}{m^3}$$

$$\left(\frac{\partial E}{\partial n}\right)_{S,V} = -\left(\frac{S}{100}\right)^3 \frac{1}{V n^2} \qquad \mu_1 = -\frac{(2.4)^3}{2.4\times10^{-6}\times 24^2}$$

$$= -10^4 \text{ J/mol}$$

c. $$dE = \left(\frac{\partial E}{\partial S}\right)_{V,n} dS + \left(\frac{\partial E}{\partial V}\right)_{S,n} dV + \left(\frac{\partial E}{\partial n}\right)_{S,V} dn$$

$$= T\,dS - p\,dV + \mu\,dn$$

d. $$dE = E_2 - E_1 = T_1\,dS - p_1\,dV + \mu_1\,dn$$

$$= 3000\times10 - 10^{11}\times1.2\times10^{-7} - 10^4\times0.5$$

$$= 1.3\times10^4 \text{ J}$$

Problem 2

a. The largest energy is transferred to the weight when the process is reversible and A and B end in mutual stable equilibrium, i.e., temperature equality

The entropy balance is

$$m_v c_v \ln \frac{T_f^A}{T_i^A} + m_g c_g \ln \frac{T_f^B}{T_i^B} = 0 \qquad T_f^A = T_f^B = T_2$$

$$5000 \times 1.8 \ln \frac{T_2}{973} + 10000 \times 1.2 \ln \frac{T_2}{673} = 0$$

$$T_2 = 673^{\frac{4}{7}} \times 973^{\frac{3}{7}} = 788\ K = 515°C$$

So the energy balance yields

$$\left(W_{if}^{AB\rightarrow}\right)_{rev} = -m_v c_v \left(T_2 - T_i^A\right) - m_g c_g \left(T_2 - T_i^B\right)$$

$$= -9000(515-700) - 12000(515-400)$$

$$= 285000\ kJ = 285\ MJ$$

b. Here the energy balance is

$$\frac{285000}{2} = -9000(T_2' - 700) - 12000(T_2' - 400)$$

$$21 T_2' = 10960 \qquad T_2' = 522°C = 795\ K$$

For this temperature, the entropy balance yields

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GENERAL THERMODYNAMICS

Problem Set 6 **Due: October 25, 1990**

1. Problem 11.2
2. Problem 11.3
3. Problem 12.7

2.451J and 22.571J

GENERAL THERMODYNAMICS

Problem Set 8 **Due: November 8, 1990**

1. Problem 17.4

2. Consider a simple system that has the surface area, a, as the only parameter, as it was introduced in Problem 17.4. In addition, it is specified that the system has only one constituent, whose amount is constant. The variation of the surface tension with temperature T for this system is given by
$\sigma = \sigma(T) = 7 \times 10^{-2}$ N m^{-1} - 10^{-4} N (mK)$^{-1}$ (T - 273.15 K). At a constant temperature of $T_0 = 400$ K, the surface area of the system increases from $a_1 = 1$ m^2 to $a_2 = 2$ m^2.

   (a) Find the Maxwell relation that follows from the Helmholtz free energy for this system.

   (b) What is the change in the entropy of the system for this constant-temperature process ?

   (c) What is the change in the internal energy of the system ?

   (d) What is the work that must be performed on the system if the process is reversible and the system experiences no work interactions other than through the change of surface area ? (Hint: What is the work for a reversible constant-temperature process of a system that has volume as the only parameter ?)

3. Problem 19.7

4. Problem 19.19

5. Problem 19.29

2.451J and 22.571J

General Thermodynamics

Midterm Examination II

November 20, 1990

Problem 1 (30/100)

A heat engine interacts with two reservoirs R_1 and R_2, at temperatures T_1 and T_2 ($T_1 > T_2$). The work done by the engine is used to drive a heat pump which interacts with reservoirs R_2 and R_3, at temperatures T_2 and T_3 ($T_3 < T_2$).

(15/100) a. If it is desired to transfer as much energy as possible out of reservoir R_3, and to use as little energy as possible out of reservoir R_1, what is the largest value of the ratio of these two energies? Express your answer in terms of T_1, T_2, and T_3.

(15/100) b. For $T_1 = 900$ K, $T_2 = 300$ K, and $T_3 = 200$ K, it is found that the ratio of the energies out of R_3 and R_1 is equal to unity, and that the heat engine operates reversibly. How much entropy is generated by irreversibility per unit of energy exchanged by reservoir R_1?

Problem 2 (30/100)

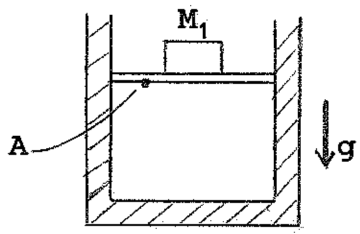
Consider two systems A and B. System A consists of 4.5 kg of air contained in a cylinder with a frictionless and massless piston of cross sectional area 0.01 m^2. The air behaves as a perfect gas with R_M = 287 J/kg K and c_p = 1 kJ/kg K, and is initially at temperature T_1^A = 4°C. On top of the piston there is a mass m_W = 700 kg. System B consists of a metal block. Its heat capacity C_B = 10 kJ/K, and its initial temperature T_1^B = 120°C.

(15/100) a. Upon interacting with each other and the mass in the earth's gravity, the air and the metal block reach mutual stable equilibrium. How much energy is exchanged between the air and the block, and how much entropy is generated by irreversibility?

(15/100) b. If cyclic machinery were interposed between the air with the weighted piston and the block, what is the largest work that can be done by the machinery?

Problem 3 (40/100)

In a well-insulated cylinder, a well-insulated, massless piston can move without friction. The area of the piston $A = 1\ m^2$, and on top of the piston lies a mass $M_1 = 10,135$ kg. The piston is in a gravity field along the axis of the cylinder of $g = 10\ m/s^2$. Vacuum prevails outside of the cylinder.



The substance within the cylinder is initially in a stable equilibrium state 1. Then an additional mass $M_2 = 9718$ kg is placed on top of the cylinder and, as a result, the system reaches a new stable equilibrium state 2. Determine state 2 if no entropy is generated, and the compressed substance is:

(15/100) a. a monatomic perfect gas with a molecular weight $M = 4$ kg/kmol at an initial temperature $T_1 = 100°C$. What are the temperature T_2 and specific volume v_2 in state 2? The universal gas constant is $R = 8.314$ J/mol K.

(10/100) b. a two-phase mixture of water vapor and liquid water with an initial quality $x_1 = 0.5$. What are the temperature T_2 and quality x_2 in state 2? Water properties are attached.

(15/100) c. a two-phase mixture of solid and liquid aluminum at $T_1 = 660.4°C$. If state 2 consists of the same two phases as state 1, what is an estimate of the temperature T_2? For aluminum at 1 bar, $h_{jf} = 3.73 \times 10^5$ J/kg and $v_{jf} = 2.625 \times 10^{-5}\ m^3/kg$.

TABLE B.14. Values of properties of water, H_2O.[a]

Properties of saturated H_2O

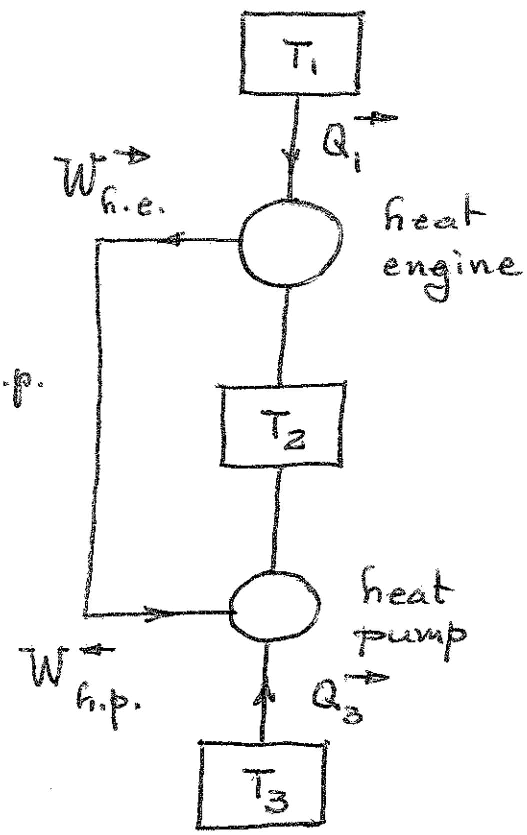
T	p	v_f	v_g	u_f	u_{fg}	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
°C	kPa	m^3/kg		kJ/kg			kJ/kg			kJ/kg K		
0.01	0.61133	0.0009997	206.14	0.0	2374.9	2374.9	0.0	2500.9	2500.9	0.0	9.1555	9.1555
5	0.87210	0.0009999	147.12	20.4	2361.4	2381.8	20.4	2489.7	2510.1	0.0741	8.9508	9.0249
10	1.2276	0.0010004	106.38	41.1	2347.6	2388.7	41.1	2478.2	2519.3	0.1478	8.7522	8.9000
15	1.7051	0.0010011	77.926	62.0	2333.6	2395.6	62.0	2466.5	2528.5	0.2207	8.5598	8.7806
20	2.3385	0.0010021	57.791	82.9	2319.6	2402.5	82.9	2454.7	2537.6	0.2928	8.3736	8.6664
25	3.1691	0.0010032	43.360	103.9	2305.4	2409.3	103.9	2442.8	2546.7	0.3640	8.1932	8.5571
30	4.2460	0.0010046	32.894	125.0	2291.1	2416.1	125.0	2430.8	2555.8	0.4341	8.0184	8.4525
35	5.6280	0.0010062	25.216	146.1	2276.8	2422.9	146.1	2418.7	2564.8	0.5032	7.8491	8.3523
40	7.3836	0.0010080	19.523	167.3	2262.4	2429.7	167.3	2406.6	2573.8	0.5712	7.6850	8.2562
45	9.5932	0.0010100	15.258	188.4	2248.0	2436.4	188.4	2394.4	2582.7	0.6381	7.5259	8.1640
50	12.349	0.0010121	12.032	209.5	2233.5	2443.0	209.5	2382.1	2591.6	0.7039	7.3716	8.0755
60	19.940	0.0010170	7.6710	251.6	2204.6	2456.2	251.6	2357.5	2609.1	0.8323	7.0764	7.9088
70	31.188	0.0010227	5.0422	293.7	2175.4	2469.1	293.7	2332.7	2626.4	0.9567	6.7978	7.7545
80	47.389	0.0010289	3.4072	335.6	2146.1	2481.7	335.7	2307.5	2643.2	1.0772	6.5342	7.6114
90	70.138	0.0010359	2.3606	377.5	2116.6	2494.1	377.6	2282.1	2659.6	1.1942	6.2841	7.4782
100	101.35	0.0010434	1.6729	419.4	2086.6	2506.1	419.5	2256.1	2675.6	1.3080	6.0460	7.3540
110	143.27	0.0010516	1.2102	461.4	2056.3	2517.6	461.5	2229.5	2691.0	1.4189	5.8189	7.2379
120	198.53	0.0010604	0.89186	503.5	2025.3	2528.8	503.7	2202.1	2705.8	1.5275	5.6013	7.1288
130	270.09	0.0010699	0.66851	545.8	1993.6	2539.4	546.1	2173.9	2720.0	1.6338	5.3923	7.0261
140	361.29	0.0010800	0.50885	588.4	1961.2	2549.6	588.8	2144.6	2733.4	1.7381	5.1910	6.9291
150	475.84	0.0010907	0.39278	631.2	1927.8	2559.1	631.8	2114.2	2746.0	1.8406	4.9964	6.8370
160	617.82	0.0011022	0.30706	674.4	1893.5	2567.9	675.1	2082.5	2757.6	1.9415	4.8079	6.7493
170	791.66	0.0011144	0.24282	718.0	1858.0	2576.0	718.8	2049.4	2768.2	2.0409	4.6246	6.6655
180	1002.1	0.0011275	0.19404	761.8	1821.4	2583.2	763.0	2014.7	2777.7	2.1388	4.4461	6.5849
190	1254.4	0.0011414	0.15653	806.1	1783.5	2589.5	807.5	1978.4	2785.9	2.2354	4.2716	6.5070
200	1553.8	0.0011564	0.12735	850.7	1744.1	2594.8	852.5	1940.2	2792.7	2.3308	4.1006	6.4314
210	1906.2	0.0011724	0.10441	895.7	1703.3	2599.0	897.9	1900.1	2798.0	2.4249	3.9326	6.3576
220	2317.8	0.0011897	0.086186	941.1	1660.7	2601.9	943.9	1857.7	2801.6	2.5181	3.7671	6.2852
230	2794.8	0.0012084	0.071577	987.1	1616.3	2603.4	990.4	1813.0	2803.4	2.6104	3.6033	6.2137
240	3344.2	0.0012287	0.059760	1033.5	1569.9	2603.4	1037.7	1765.6	2803.3	2.7020	3.4408	6.1428
250	3972.9	0.0012509	0.050123	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7932	3.2788	6.0720
260	4688.5	0.0012753	0.042202	1128.7	1469.8	2598.5	1134.7	1661.6	2796.3	2.8843	3.1167	6.0009
270	5498.6	0.0013023	0.035641	1177.7	1415.4	2593.1	1184.8	1604.3	2789.1	2.9755	2.9536	5.9291
280	6411.6	0.0013323	0.030168	1227.8	1357.7	2585.5	1236.3	1542.6	2778.9	3.0672	2.7888	5.8560
290	7435.9	0.0013659	0.025568	1279.3	1296.1	2575.4	1289.4	1476.1	2765.5	3.1599	2.6212	5.7811
300	8580.9	0.0014040	0.021673	1332.3	1230.0	2562.4	1344.4	1403.9	2748.3	3.2539	2.4495	5.7034
310	9856.4	0.0014479	0.018349	1387.3	1158.5	2545.8	1401.6	1325.0	2726.6	3.3496	2.2722	5.6219
320	11274	0.0014991	0.015486	1444.6	1080.3	2524.9	1461.5	1237.9	2699.4	3.4479	2.0871	5.5350
330	12845	0.0015606	0.012996	1504.9	993.4	2498.3	1524.9	1140.3	2665.2	3.5499	1.8906	5.4405
340	14586	0.0016373	0.010797	1569.3	894.6	2463.9	1593.2	1028.2	2621.4	3.6576	1.6769	5.3345
350	16513	0.0017396	0.0088132	1640.5	777.2	2417.8	1669.3	894.0	2563.3	3.7754	1.4347	5.2101
360	18651	0.0018942	0.0069457	1725.0	625.9	2350.9	1760.4	720.1	2480.4	3.9142	1.1373	5.0515
370	21027	0.0022178	0.0049282	1847.9	380.3	2228.1	1894.5	437.2	2331.7	4.1167	0.6798	4.7965
374.14	22089	0.0031550	0.0031550	2029.1	0.0	2029.1	2098.8	0.0	2098.8	4.4289	0.0000	4.4289

[a] Data generated using the correlations in W. C. Reynolds, *Thermodynamic Properties in SI*, Dept. of Mech. Eng., Stanford University, Stanford, CA, 1979.

2.451 J and 22.571 J

Solution midterm examination, 11/20/90

Problem 1



a.

$$W^{\rightarrow}_{h.e.} = \left(1 - \frac{T_2}{T_1}\right) Q_1^{\rightarrow} - T_2 (S_{irr})_{h.e.}$$

$$Q_3^{\rightarrow} = \frac{T_3}{T_2 - T_3} W^{\leftarrow}_{h.p.} - \frac{T_2 T_3}{T_2 - T_3} (S_{irr})_{h.p.}$$

$$W^{\rightarrow}_{h.e.} = W^{\leftarrow}_{h.p.}$$

For the optimum ratio, the heat engine and the heat pump must be reversible. So

$$\left(\frac{Q_3^{\rightarrow}}{Q_1^{\rightarrow}}\right)_{opt} = \frac{1 - \frac{T_2}{T_1}}{\frac{T_2}{T_3} - 1} = \frac{1 - (1/3)}{(3/2) - 1} = \underline{4/3}$$

b. When the heat engine is reversible, and the heat pump irreversible,

$$\frac{Q_3^{\rightarrow}}{Q_1^{\rightarrow}} = 1 = \frac{T_3}{T_2 - T_3} \cdot \left(1 - \frac{T_2}{T_1}\right) - \frac{T_2 T_3}{T_2 - T_3} (S_{irr})_{h.p.} \frac{1}{Q_1^{\rightarrow}}$$

So $\frac{T_2(S_{irr})_{h.p.}}{Q_1^{\rightarrow}} = 1 - \frac{T_2}{T_1} - \frac{T_2 - T_3}{T_3} = 1 - \frac{1}{3} - \frac{3}{2} + 1 = \frac{1}{6}$

or $(S_{irr})_{h.p.} / Q_1^{\rightarrow} = 1/6 \times 300 = \underline{1/1800 \ K^{-1}}$.

Problem 2

The weight on top of A maintains a constant pressure p_1. So the change in energy of A plus the work done on the weight equals

$$m_A c_v (T_2^A - T_1^A) + p_1 (V_2^A - V_1^A) = m_A (c_v + R)(T_2^A - T_1^A)$$

$= m_A c_p (T_2^A - T_1^A)$ because $pV = mRT$ for the gas in A. The energy balance yields

$$m_A c_p (T_2^A - T_1^A) + C_B (T_2^B - T_1^B) = - W^{\rightarrow}_{machinery}$$

and the entropy balance

$$m_A c_p \ln (T_2^A / T_1^A) + C_B \ln (T_2^B / T_1^B) = S_{irr}$$

a. At mutual stable equilibrium $T_2^A = T_2^B = T_2$, $W^{\rightarrow} = 0$ (no machinery). So the energy balance yields

$$T_2 = \frac{m_A c_p T_1^A + C_B T_1^B}{m_A c_p + C_B} = \underline{84°C}$$

The energy transfer out of the block is $\underline{360 \text{ kJ}}$

and the entropy balance yields $S_{irr} = 0.18 \ kJ/kg\,K$.

b. For largest work, again $T_2^A = T_2^B = T_2$ but $S_{irr} = 0$

So the entropy balance yields

$$T_2 = \left[(T_1^A)^{m_A c_p} (T_1^B)^{C_B} \right]^{1/(m_A c_p + C_B)} = 352.6 \ K$$

$$= \underline{79^\circ C}$$

and the energy balance

$$W^{\rightarrow}_{machinery} = \underline{72.5 \ kJ}.$$

Problem 3

a. The gas constant of the substance is

$$R_M = R/M = 8.314 \ (kJ/kmol\,K)/4 \ (kg/kmol)$$
$$= 2.079 \ kJ/kg\,K$$

For isentropic compression

$$\underline{v_2 = v_1 \left(\frac{p_1}{p_2} \right)^{1/\gamma}}$$

where $v_1 = R_M T_1 / p_1$ and $\gamma = \frac{5}{3} = 1.667 = \frac{c_p}{c_v}$

Moreover

$$\underline{T_2 = T_1 \left(\frac{p_1}{p_2} \right)^{-(\gamma-1)/\gamma}}$$

So $$v_2 = \frac{2079 \times 373.15}{1.014 \times 10^5} \times \left(\frac{1.014}{1.985}\right)^{3/5} = \underline{5.11 \ m^3/kg}$$

$$T_2 = 373.15 \times \left(\frac{1.014}{1.985}\right)^{-0.4} = \underline{488.2 \ K}$$

b. From the data we find for $\underline{p_2 = 198.53 \ kPa}$

$\underline{T_2 = 120°C = 393.15 \ K}$.

So the final quality

$$x_2 = \frac{s_i - (s_f)_2}{(s_{fg})_2} = \frac{4.331 - 1.5275}{5.6013} = 0.5005$$

c. We can estimate the final temperature by using the Clapeyron relation

$$\frac{dT}{dp} = \frac{v_{if}}{s_{if}} = T\frac{v_{if}}{h_{if}} = 933.55 \times \frac{2.625 \times 10^{-5}}{3.73 \times 10^5} =$$

$$= 6.57 \times 10^{-8} \ K/Pa$$

Upon writing $dT/dp \sim \Delta T/\Delta p$ we find

$$\Delta T \simeq \left(\frac{dT}{dp}\right)\Delta p = 6.57 \times 10^{-8} \times 97180 = 0.0064 \ K$$

$\underline{T_2 = T_1 + 0.0064}$ for T_1 in K

2.451J and 22.571J

GENERAL THERMODYNAMICS

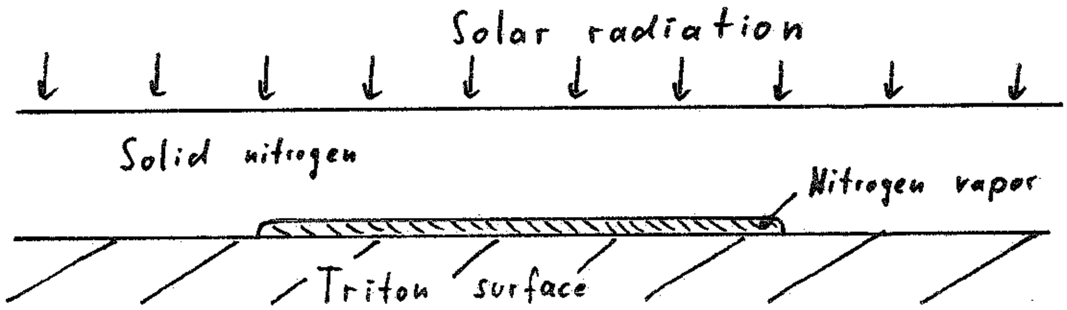
Problem Set 9 **Due: November 15, 1990**

1. Problem ?

2. Problem ?

3. Problem ?

4. As discussed in the attached article, the spacecraft *Voyager 2* observed plumes on the surface of Triton, Neptune's largest moon (See also *Science*, 1990, Vol. 250, pp. 410 - 443). One hypothesis for this phenomenon assumes that the absorption of solar radiation in the solid-nitrogen layer covering the Triton surface leads to the formation of nitrogen vapor pockets. If the vapor pressure in a pocket exceeds the burst pressure of the solid-nitrogen layer, then the vapor is assumed to escape suddenly, thus forming a nitrogen geyser. From other *Voyager 2* measurements, it is known that the outer surface temperature of Triton is approximately 40 K. In the following, we will develop a very simple model for this process, based on the schematic below.



(a) Show that the sublimation pressure curve, which gives the pressure as a function of temperature for solid-vapor two-phase mixtures in stable equilibrium states, can be approximated by

$$\ln\left(\frac{p}{p_{tp}}\right) \approx \frac{h_{jg}}{R_M}\left(\frac{1}{T_{tp}} - \frac{1}{T}\right)$$

where R_M is the specific gas constant of the vapor, and p_{tp} and T_{tp} are triple point pressure and temperature, respectively. Hint: Start with the Clausius-Clapeyron relation. Neglect terms that are small compared to others. Model the vapor as an ideal gas (a very rough approximation).

(b) You find thermodynamic properties of nitrogen in Tables B1, B.2, B.3 and B.13 of the textbook. If the solid and vapor are both at 40 K, what process leads to the vapor formation ? Estimate the specific latent heat for this process.

(c) Based on your result in (b), estimate the vapor production rate, mass per unit time, per unit Triton surface area, if the solar energy flux causing the vapor production is 0.4 W/m^2 at the Tripton surface.

(d) Using the result in (a), determine the pressure in the vapor pocket if both vapor and solid are in mutual stable equilibrium at 40 K.

(e) Assume that the burst pressure of the ice layer is $p_b = 5000$ Pa, and model the vapor as an ideal gas. Starting at the state of part (b), how much vapor must be produced, if the pocket has a diameter of 50 m, and a thickness of 10 cm, to make the ice layer burst ? How long will this take ?

Solar-system exploration

Plume de ma Triton

PLANETARY scientists are famous for making little spacecraft go a long way; they can do the same trick with data, too. When *Voyager* 2 whipped around Triton, Neptune's largest moon, last summer, it sent back only 100 or so photos, of which a mere handful were close-ups of the surface. Careful inspection showed that those pictures held a big surprise: dark plumes towering 8km above the surface, then being spread out by the jet-stream winds into long thin clouds. Scientists at JPL, the laboratory in Pasadena, California, that ran the *Voyager* programme, excitedly decided that they had found the first extraterrestrial geysers. They were justifiably pleased about finding an explanation for such an oddity. Now they have surpassed themselves, and come up with other possible explanations, as well.

If the plumes are geysers, what drives them? Earthly geysers are powered by heat from deep within the earth; but most of the warmth in Triton's rocky core has already been lost. If the heat is not coming from below, perhaps it comes from above—from the sun. Triton's surface is largely covered with frozen nitrogen. A clear layer of frozen nitrogen a metre or two thick, covering a darker layer—perhaps of hydrocarbons—could act as a greenhouse. Heat could get in but not out. The dark layer warms up and some of the frozen nitrogen turns to gas. That gas then erupts through the ice as a geyser.

Various forms of the geyser hypothesis were recently discussed in *Science*. Some think that the gas erupts at high speed; others that it seeps out but climbs into the sky because it is warmer (and thus lighter) than the atmosphere (which is also nitrogen). Heat and gas may well move around under the insulating ice, allowing a large greenhouse to feed a small geyser, and thus allowing long eruptions. If the nitrogen greenhouse is thicker and has no dark layer below it, it might provide enough heat and pressure for reservoirs of liquid nitrogen, which could lead to particularly violent eruptions. If the moon's internal heat reaches the ice layer unevenly, concentrated at a few hot spots, it too might create such explosive subtritonian lakes.

There is an alternative to geysers. Dr Andrew Ingersoll and Dr Kimberly Tryka, of the California Institute of Technology, suggest that the plumes may be dust-devils, carrying heat and muck into the upper atmosphere. They take their idea from the fact that studies of radio signals from *Voyager*, which passed through Triton's atmosphere, seem to show that it is warmer than the ice of the surface. Dr Ingersoll and Dr Tryka point out that dark iceless spots on the surface can be warmed by the sun, and that cold gas above these spots could form little whirlwinds, just as cold desert air can.

The idea has its charm. Dust devils could stay thin and focused as they rise 8km, whereas jets from geysers might be expected to spread out. They could also provide the heat to warm the atmosphere. Unfortunately many scientists have doubts about the warm atmosphere. They want to do more detailed analyses of the radio data. It is also unclear how winds in an atmosphere as thin as Triton's—100,000 times thinner than the earth's—could lift up the dark substances seen in the plumes.

The solar-powered geysers have their drawbacks, as well. If the frozen nitrogen takes the form of fluffy opaque frost, rather than solid, clear ice, it does not work as a greenhouse. Studies of how nitrogen behaves at very low temperatures and pressures might help to sort that out. Further study of *Voyager*'s meagre messages may also help. The best answer, though, is to take another look. Around 2001 the planets will be arranged so that a probe could be launched into orbit around Neptune, rather than just flying past it as *Voyager* did. It would not get there until about 2014, though—by which time the scientists now poring over the plumes may be past caring.

Thar she blows

Solution

(a) Clausius - Clapeyron relation

$$\frac{dp}{dT} = \frac{1}{T} \frac{h_g - h_f}{v_g - v_f} \qquad (1)$$

Assume $v_f \approx v_f$. Assume further that $v_g >> v_f$.

Recall ideal-gas equation of state,

$$pv = R_M T \qquad (2)$$

and substitute in (1), to find

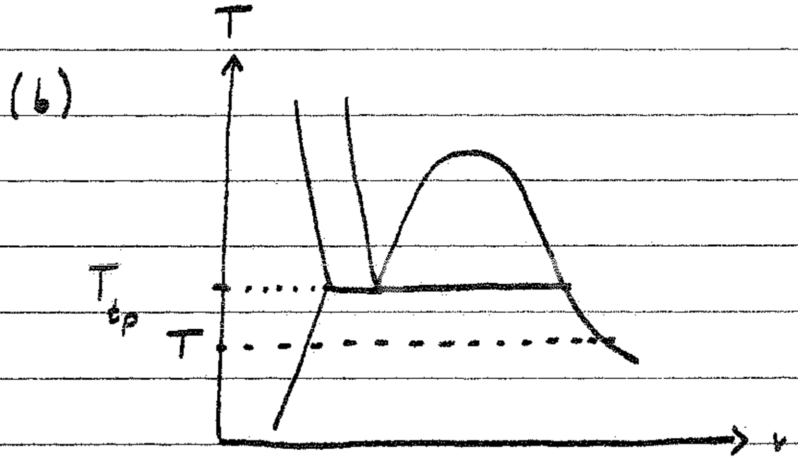
$$\frac{dp}{dT} \approx \frac{p\, h_{fg}}{R_M T^2} \qquad (3)$$

and upon integration,

$$\ln\left(\frac{p}{p_{tp}}\right) \approx \frac{h_{fg}}{R_M}\left(\frac{1}{T_{tp}} - \frac{1}{T}\right) \qquad (4)$$

q.e.d.

(b)



For nitrogen, $T_{tp} = 63.2$ K, and for $T < T_{tp}$, the phase change is a sublimation process.

From Table B.13, in the vicinity of the triple point, $h_{fg} = 214.83$ kJ/kg. From Table B.3, at $p = 1$ bar, $h_{if} = 25.7$ kJ/kg. Assume that $h_{if}(p_{tp}) \approx h_{if}(p = 1\text{ bar})$.

Recall that in the vicinity of the triple point, $h_{ig} = h_{if} + h_{fg}$. Hence, $h_{ig} \approx 240.5 \times 10^3$ J/kg.

Assume that for $T < T_{tp}$, $h_{ig} \neq h_{ig}(T)$.

(c) The sublimation rate per unit Tripton surface area is $(\dot{m}/A) = \frac{(\dot{E}/A)}{h_{jg}} = \frac{0.4\ W/m^2}{240.5 \times 10^3\ J/kg}$

$(\dot{m}/A) = 1.66 \times 10^{-6}$ kg/s

(d) For nitrogen, $M = 28.013$ kg/kmol.

Hence, $R_M = R/M = 8.3145 \frac{J}{mol\,K} / (28.013\ kg/kmol)$

$R_M = 296.8 \frac{J}{kg\,K}$

From Table B.1, $p_{tp} = 12.6$ kPa

Substitute T=40 K into equation (4), to find

$p_{j,sat}\,(T = 40\ K) = 7.43$ Pa

(e) Recall $pV = m R_M T$

Assume that during the sublimation process, the system consisting of ice and vapor passes through stable equilibrium states.

Then the temperature at the burst pressure is $T(p_b) = T_{j,sat}(p_b)$ and can be calculated from equation (4),

$$T(p_b) = 58.95\ K$$

At the burst pressure, $m(p_b) = \dfrac{p_b V}{R_M T}$

$$= \frac{5000\ Pa \times \frac{\pi}{4}\, 2500\ m^2 \times 0.1\ m}{296.8\ J/kg\,K \times 58.95\ K}$$

$$= 56.1\ kg$$

At the initial pressure, $m(T = 40K) = \dfrac{7.43\ Pa \times 196.3\ m^3}{296.8\ J/kg\,K \times 40\ K}$

$$= 0.123\ kg$$

The mass of vapor to be generated is $\Delta m = 55.98\ kg$

With the sublimation rate of part (c), and an area of $A = 1963\ m^2$, the time up to the burst is

$$t_b = \frac{\Delta m}{(\dot{m}/A)\,A} = \frac{55.98\ kg\ m^2}{1.66 \times 10^{-6}\ kg/s\ \ 1963\ m^2} = 1.7 \times 10^4\ s = 4.8\ hours$$

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Litho in U.S.A.

Note that this simple calculation assumes the volume of the vapor pocket to be constant, which is a very rough assumption

2.451J and 22.571J

GENERAL THERMODYNAMICS

Problem Set 10 | Due November 29, 1990

1. Problem 22.4

2. Problem 22.8

3. Problem 22.9

4. Problem 23.6

5. Problem 23.12

2.451J and 22.571J

GENERAL THERMODYNAMICS

Problem Set 11 Due December 6, 1990

1. Problem 24.3

2. Problem 24.17

3. Problem 24.20

4. Problem 25.6

Monday, December 17, 1990 Time: 1:30–4:30 p.m.

Massachusetts Institute of Technology

Scheduled Examination in

General Thermodynamics

2.451J and 22.571J

Note: Students are not permitted to use any books, notebooks, or papers during the course of this examination. Each student is permitted to have a few–page personal summary of key concepts and formulas.

Problem 1 (10/135)

(5/135) a. Write the first law of thermodynamics.

(5/135) b. Write the second law of thermodynamics for systems without chemical and nuclear reactions altering the amounts of constituents.

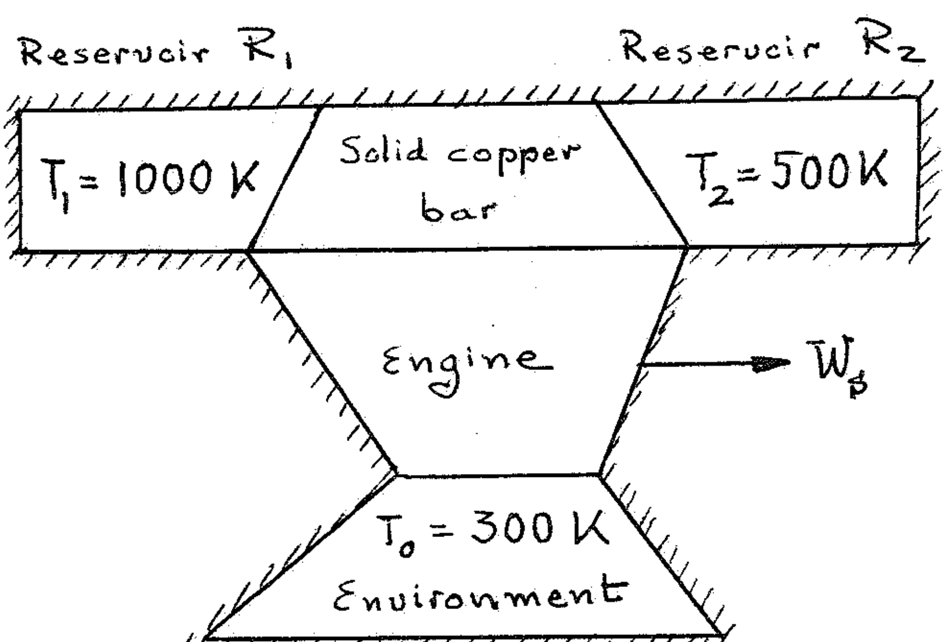
Problem 2 (30/135)

A solid copper bar interacts only with two reservoirs R_1 and R_2 at $T_1 = 1000$ K and $T_2 = 500$ K, and a cyclic engine as shown in the sketch. In addition, the engine delivers shaft work to a weight and interacts with the environment at $T_0 = 300$ K. The energy transfer out of R_1 is $Q^{R_1\rightarrow} = 7000$ kJ, the entropies generated by irreversibility in the solid copper bar $\left[S_{irr}\right]_s = 7$ kJ/K and in the cyclic engine $\left[S_{irr}\right]_e = 2$ kJ/K. The entropy transfer into R_2 is $S^{R_2\leftarrow} = 4$ kJ/K.

(5/135) a. Find the work equivalent of the energy transfer out of R_1.

(15/135) b. Find the work done by the cyclic engine.

(10/135) c. Find the effectiveness (thermodynamic efficiency) with which $Q^{R_1\rightarrow}$ is utilized.



Problem 3 (30/135)

A boiler operates in steady state at a constant pressure of 200 bar and a water flow rate of 100 kg/s. The water enters and leaves the boiler at temperatures of 100 °C and 500 °C, respectively. The boiler experiences a heat interaction at $T_Q = 1000$ °C, and the temperature of the environment is $T_0 = 25$ °C. The properties of water at 200 bar are attached.

(5/135) a. What is the rate of heat into the boiler ?

(15/135) b. What is the rate of lost work due to irreversibility ?

(10/135) c. What is the change in the availability rate of the water ?

Properties of H_2O

$p = 10$ MPa

T (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg K)	c_v (kJ/kg K)	c_p (kJ/kg K)
0	0.000995	−0.3	9.6	−0.0005	4.163	4.163
50	0.001008	207.4	217.4	0.6983	3.994	4.155
100	0.001039	415.7	426.0	1.2984	3.759	4.194
200	0.001148	844.1	855.5	2.3170	3.331	4.447
Sat. liq.	0.001453	1393.3	1407.8	3.3599	3.098	6.140
311.06	0.01657	1150.5	1316.2	2.2530		
Sat. vap.	0.01802	2543.8	2724.0	5.6129	3.048	7.014
350	0.02242	2698.6	2922.8	5.9433	2.323	4.022
400	0.02641	2831.8	3095.9	6.2109	1.999	3.082
500	0.03279	3045.2	3373.1	6.5956	1.849	2.589
600	0.03837	3241.2	3624.8	6.9020	1.849	2.470
700	0.04358	3434.2	3870.0	7.1678	1.879	2.442
800	0.04860	3628.5	4114.4	7.4069	1.920	2.450
900	0.05350	3825.8	4360.8	7.6264	1.967	2.479
1000	0.05833	4027.3	4610.6	7.8307	2.017	2.519

$p = 20$ MPa

T (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg K)	c_v (kJ/kg K)	c_p (kJ/kg K)
0	0.000990	−0.2	19.6	−0.0004	**4.128**	4.128
50	0.001003	205.9	226.0	0.6937	**3.970**	4.134
100	0.001034	412.9	433.6	1.2909	**3.744**	4.173
200	0.001139	837.3	860.0	2.3023	**3.320**	4.399
300	0.001360	1305.7	1332.8	3.2063	**3.052**	5.314
Sat. liq.	0.002041	1787.5	1828.3	4.0169	**3.439**	22.81
365.81	0.003794	505.0	580.9	0.9091		
Sat. vap.	0.005835	2292.5	2409.2	4.9260	**4.070**	44.68
400	0.009943	2618.6	2817.4	5.5528	**2.700**	6.327
500	0.01477	2942.2	3237.6	6.1391	**2.045**	3.274
600	0.01818	3173.4	3537.0	6.5038	**1.964**	2.808
700	0.02113	3385.9	3808.6	6.7984	**1.959**	2.646
800	0.02386	3592.2	4069.3	7.0535	**1.971**	2.579
900	0.02645	3796.9	4325.9	7.2821	**1.994**	2.559
1000	0.02897	4002.6	4582.0	7.4916	**2.026**	2.567

Problem 4 (40/135)

In many chemical processing plants, a hot stream must be cooled and a cold stream must be heated. One method of achieving these two tasks is by having the two streams interact in a heat exchanger. Another is by making the two streams interact via work delivering machinery and, if necessary, allowing the machinery to interact also with the environment at $T_0 = 293$ K.

Consider: (a) a hot stream of a perfect gas ($c_p = 1$ kJ/kg K, $R_M = 0.286$ kJ/kg K) at $T_{g1} = 750$ K and $p_{g1} = 60$ atm which must be cooled to $T_{g2} = 310$ K, and the pressure of which must be reduced to $p_{g2} = 1$ atm; and (b) a cold stream of water at $T_{w1} = 20°$C and $p_{w1} = 1$ bar which must be transformed to superheated steam at $T_{w2} = 420°$C and $p_{w2} = p_{w1}$. The required pressure drop of the stream being cooled is achieved by a throttle at the exit of the heat exchanger. Useful properties of water are attached.

(10/135)	a.	How much superheated steam can be raised in the heat exchanger per kilogram of gas cooled?
(15/100)	b.	If instead of the heat exchanger and throttle, work producing machinery is used, what is the largest amount of work per kilogram of gas cooled as specified, and for raising the same amount of steam as in part (a)?
(10/100)	c.	How much entropy is generated by irreversibility in part (a)?
(5/100)	d.	What is the effectiveness of the heat exchanger in part (a)?

Table 4. Liquid

p (t Sat.)	0				25 (223.99)				50 (263.99)			
t	v	u	h	s	v	u	h	s	v	u	h	s
Sat.					1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202
0	1.0002	-.03	-.03	-.0001	.9990	-.00	2.50	-.0000	.9977	.04	5.04	.0001
20	1.0018	83.95	83.95	.2966	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0078	167.56	167.56	.5725	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
60	1.0172	251.12	251.12	.8312	1.0160	250.67	253.21	.8298	1.0149	250.23	255.30	.8285
80	1.0291	334.87	334.87	1.0753	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0436	418.96	418.96	1.3069	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
120	1.0604	503.57	503.57	1.5278	1.0590	502.68	505.33	1.5255	1.0576	501.80	507.09	1.5233
140	1.0800	588.89	588.89	1.7395	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
160	1.1024	675.19	675.19	1.9434	1.1006	673.90	676.65	1.9404	1.0988	672.62	678.12	1.9375
180	1.1283	762.72	762.72	2.1410	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1581	851.8	851.8	2.3334	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
210	1.1749	897.1	897.1	2.4281	1.1720	895.0	898.0	2.4238	1.1691	893.0	898.8	2.4195
220	1.1930	943.0	943.0	2.5221	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
230	1.2129	989.6	989.6	2.6157	1.2092	987.0	990.1	2.6105	1.2056	984.5	990.6	2.6055
240	1.2347	1037.1	1037.1	2.7091	1.2305	1034.2	1037.2	2.7034	1.2264	1031.4	1037.5	2.6979
250	1.2590	1085.6	1085.6	2.8027	1.2540	1082.3	1085.4	2.7964	1.2493	1079.1	1085.3	2.7902
260	1.2862	1135.4	1135.4	2.8970	1.2804	1131.6	1134.8	2.8898	1.2749	1127.9	1134.3	2.8830
270	1.3173	1186.8	1186.8	2.9926	1.3102	1182.4	1185.7	2.9844	1.3036	1178.2	1184.7	2.9766
280	1.3535	1240.4	1240.4	3.0904	1.3447	1235.1	1238.5	3.0808	1.3365	1230.2	1236.8	3.0717
290	1.3971	1297.0	1297.0	3.1918	1.3855	1290.5	1294.0	3.1801	1.3750	1284.4	1291.3	3.1693
300	1.4520	1358.1	1358.1	3.2992	1.4357	1349.6	1353.2	3.2843	1.4214	1341.9	1349.0	3.2708
310									1.4803	1404.1	1411.5	3.3789

p (t Sat.)	75 (290.59)				100 (311.06)				125 (327.89)			
t	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	1.3677	1282.0	1292.2	3.1649	1.4524	1393.0	1407.6	3.3596	1.5466	1492.2	1511.5	3.5286
0	.9965	.06	7.54	.0002	.9952	.09	10.04	.0002	.9940	.13	12.56	.0003
20	.9984	83.50	90.99	.2950	.9972	83.36	93.33	.2945	.9961	83.21	95.67	.2940
40	1.0045	166.64	174.18	.5696	1.0034	166.35	176.38	.5686	1.0024	166.05	178.58	.5676
60	1.0138	249.79	257.40	.8272	1.0127	249.36	259.49	.8258	1.0116	248.94	261.58	.8245
80	1.0256	333.15	340.84	1.0704	1.0245	332.59	342.83	1.0688	1.0233	332.03	344.82	1.0672
100	1.0397	416.81	424.62	1.3011	1.0385	416.12	426.50	1.2992	1.0373	415.42	428.39	1.2973
120	1.0562	500.94	508.86	1.5211	1.0549	500.08	510.64	1.5189	1.0535	499.24	512.41	1.5167
140	1.0752	585.72	593.78	1.7317	1.0737	584.68	595.42	1.7292	1.0722	583.66	597.07	1.7267
160	1.0970	671.37	679.59	1.9346	1.0953	670.13	681.08	1.9317	1.0935	668.91	682.58	1.9288
180	1.1219	758.13	766.55	2.1308	1.1199	756.65	767.84	2.1275	1.1178	755.19	769.16	2.1242
200	1.1505	846.3	854.9	2.3216	1.1480	844.5	856.0	2.3178	1.1456	842.8	857.1	2.3141
210	1.1664	891.0	899.8	2.4154	1.1637	889.1	900.7	2.4113	1.1610	887.1	901.6	2.4073
220	1.1835	936.2	945.1	2.5083	1.1805	934.1	945.9	2.5039	1.1776	932.0	946.7	2.4995
230	1.2022	982.1	991.1	2.6006	1.1988	979.7	991.7	2.5958	1.1955	977.4	992.3	2.5911
240	1.2225	1028.6	1037.8	2.6925	1.2187	1026.0	1038.1	2.6872	1.2150	1023.4	1038.5	2.6821
250	1.2448	1076.0	1085.3	2.7843	1.2405	1073.0	1085.4	2.7785	1.2363	1070.1	1085.6	2.7729
260	1.2696	1124.4	1134.0	2.8763	1.2645	1121.1	1133.7	2.8699	1.2597	1117.8	1133.5	2.8637
270	1.2973	1174.1	1183.9	2.9691	1.2913	1170.3	1183.2	2.9618	1.2857	1166.5	1182.6	2.9548
280	1.3288	1225.4	1235.4	3.0631	1.3216	1220.9	1234.1	3.0548	1.3148	1216.6	1233.0	3.0469
290	1.3653	1278.8	1289.0	3.1591	1.3564	1273.4	1287.0	3.1495	1.3481	1268.4	1285.2	3.1404
300	1.4087	1334.9	1345.4	3.2584	1.3972	1328.4	1342.3	3.2469	1.3867	1322.3	1339.6	3.2361
310	1.4622	1394.9	1405.8	3.3629	1.4465	1386.6	1401.1	3.3485	1.4326	1379.1	1397.0	3.3353
320	1.5330	1461.1	1472.6	3.4764	1.5093	1449.8	1464.9	3.4569	1.4895	1439.9	1458.5	3.4399
330					1.5972	1521.5	1537.5	3.5783	1.5646	1507.1	1526.6	3.5538
340									1.6795	1586.9	1607.9	3.6874

1 Bar = 1.01972 kg./sq.cm.; 1 Joule = 1/4.1868 I.T.Cal.

Table 3. Vapor

t \ p (t Sat.)	.90 (96.71) v	u	h	s	.95 (98.20) v	u	h	s	1.0 (99.63) v	u	h	s
Sat.	1869.5	2502.6	2670.9	7.3949	1777.3	2504.4	2673.2	7.3767	1694.0	2506.1	2675.5	7.3594
50	1610.9	2430.0	2574.9	7.1175	1523.6	2429.1	2573.8	7.0898	1445.0	2428.2	2572.7	7.0633
55	1639.3	2437.8	2585.4	7.1495	1550.6	2437.0	2584.3	7.1219	1470.8	2436.1	2583.2	7.0956
60	1667.4	2445.7	2595.7	7.1809	1577.4	2444.9	2594.7	7.1535	1496.4	2444.1	2593.7	7.1274
65	1695.4	2453.5	2606.1	7.2118	1604.3	2452.7	2605.1	7.1845	1521.9	2452.0	2604.2	7.1586
70	1723.2	2461.3	2616.4	7.2420	1630.6	2460.6	2615.5	7.2150	1547.1	2459.9	2614.6	7.1892
75	1750.9	2469.1	2626.7	7.2718	1656.9	2468.4	2625.8	7.2449	1572.2	2467.8	2625.0	7.2192
80	1778.4	2476.9	2636.9	7.3010	1683.0	2476.2	2636.1	7.2742	1597.2	2475.6	2635.3	7.2487
85	1805.8	2484.6	2647.1	7.3296	1709.1	2484.0	2646.4	7.3030	1622.0	2483.4	2645.6	7.2776
90	1833.1	2492.3	2657.3	7.3578	1735.0	2491.7	2656.6	7.3313	1646.8	2491.2	2655.9	7.3061
95	1860.2	2500.0	2667.4	7.3855	1760.8	2499.5	2666.7	7.3591	1671.3	2498.9	2666.1	7.3340
100	1887.3	2507.7	2677.5	7.4128	1786.5	2507.2	2676.9	7.3865	1695.8	2506.7	2676.2	7.3614
110	1941.1	2522.9	2697.6	7.4659	1837.6	2522.5	2697.0	7.4398	1744.5	2522.0	2696.5	7.4149
120	1994.5	2538.1	2717.6	7.5174	1888.4	2537.7	2717.1	7.4915	1792.9	2537.3	2716.6	7.4668
130	2047.7	2553.2	2737.5	7.5674	1938.9	2552.9	2737.1	7.5416	1840.9	2552.5	2736.6	7.5170
140	2100.6	2568.3	2757.4	7.6160	1989.1	2568.0	2756.9	7.5903	1888.7	2567.7	2756.5	7.5659
150	2153.	2583.3	2777.1	7.6634	2039	2583.0	2776.8	7.6377	1936.4	2582.8	2776.4	7.6134
160	2206.	2598.4	2796.9	7.7095	2089.	2598.1	2796.6	7.6839	1983.8	2597.8	2796.2	7.6597
170	2258.	2613.4	2816.6	7.7545	2139	2613.1	2816.3	7.7290	2031.1	2612.9	2816.0	7.7048
180	2311.	2628.4	2836.3	7.7985	2188	2628.2	2836.1	7.7731	2078.2	2627.9	2835.8	7.7489
190	2363	2643.4	2856.0	7.8415	2238	2643.2	2855.8	7.8162	2125.3	2643.0	2855.5	7.7921
200	2415	2658.4	2875.8	7.8837	2287	2658.2	2875.5	7.8584	2172	2658.1	2875.3	7.8343
210	2467	2673.5	2895.5	7.9247	2337	2673.3	[illegible]	7.8996	2219	2673.1	2895.1	7.8756
220	2519	2688.6	2915.2	7.9654	2386	2688.4	[illegible]	7.9401	2266.	2688.2	2914.8	7.9162
230	2571	2703.7	2935.0	8.0051	2435	2703.5	2934.8	7.9799	2313	2703.4	2934.6	7.9559
240	2623	2718.8	2954.8	8.0441	2484	2718.7	2954.7	8.0189	2359	2718.5	2954.5	7.9949
250	2674	2734.0	2974.7	8.0824	2533	2733.9	2974.5	8.0572	2406	2733.7	2974.3	8.0333
260	2726	2749.2	2994.6	8.1200	2582	2749.1	2994.4	8.0948	2453	2749.0	2994.3	8.0710
270	2778	2764.5	3014.5	8.1571	2631	2764.4	3014.3	8.1319	2499	2764.3	3014.2	8.1080
280	2829	2779.8	3034.5	8.1935	2680	2779.7	3034.3	8.1684	2546	2779.6	3034.2	8.1445
290	2881	2795.2	3054.5	8.2294	2729	2795.1	3054.4	8.2043	2592	2795.0	3054.2	8.1804
300	2933	2810.6	3074.6	8.2647	2778	2810.5	3074.4	8.2396	2639	2810.4	3074.3	8.2158
320	3036	2841.6	3114.8	8.3338	2876	2841.5	3114.7	8.3087	2732	2841.5	3114.6	8.2849
340	3139	2872.9	3155.4	8.4010	2973	2872.8	3155.3	8.3759	2824	2872.7	3155.2	8.3521
360	3242	2904.3	3196.1	8.4664	3071	2904.3	3196.0	8.4413	2917	2904.2	3195.9	8.4175
380	3345.	2936.0	3237.1	8.5301	3169	2936.0	3237.0	8.5051	3010	2935.9	3236.9	8.4813
400	3448.	2968.0	3278.3	8.5923	3266	2967.9	3278.2	8.5672	3103	2967.9	3278.2	8.5435
420	3551.	3000.2	3319.8	8.6530	3364.	3000.2	3319.7	8.6279	3195.	3000.1	3319.6	8.6042
440	3654.	3032.7	3361.5	8.7123	3461.	3032.6	3361.4	8.6873	3288.	3032.6	3361.4	8.6636
460	3756.	3065.4	3403.5	8.7704	3558.	3065.4	3403.4	8.7454	3380.	3065.3	3403.4	8.7216
480	3859.	3098.4	3445.7	8.8272	3656.	3098.4	3445.7	8.8022	3473.	3098.3	3445.6	8.7785
500	3962.	3131.7	3488.2	8.8829	3753	3131.6	3488.2	8.8579	3565	3131.6	3488.1	8.8342
520	4065.	3165.2	3531.0	8.9375	3851	3165.1	3531.0	8.9125	3658.	3165.1	3530.9	8.8888
540	4167.	3199.0	3574.0	8.9911	3948	3199.0	3574.0	8.9661	3750.	3198.9	3574.0	8.9424
560	4270.	3233.0	3617.4	9.0437	4045	3233.0	3617.3	9.0188	3843	3233.0	3617.3	8.9950
580	4373.	3267.4	3660.9	9.0954	4143	3267.4	3660.9	9.0704	3935.	3267.3	3660.9	9.0467
600	4476	3302.0	3704.8	9.1462	4240	3302.0	3704.8	9.1213	4028	3301.9	3704.7	9.0976
620	4578.	3336.9	3748.9	9.1962	4337	3336.9	3748.9	9.1712	4120	3336.8	3748.9	9.1475
640	4681	3372.1	3793.3	9.2454	4434	3372.0	3793.3	9.2204	4213	3372.0	3793.3	9.1967
660	4784.	3407.5	3838.0	9.2938	4532	3407.5	3838.0	9.2688	4305	3407.4	3838.0	9.2451
680	4886.	3443.2	3883.0	9.3415	4629.	3443.2	3883.0	9.3165	4397	3443.2	3882.9	9.2928
700	4989.	3479.2	3928.2	9.3884	4726	3479.2	3928.2	9.3635	4490.	3479.2	3928.2	9.3398
750	5245	3570.5	4042.6	9.5030	4969	3570.5	4042.5	9.4780	4721	3570.4	4042.5	9.4544
800	5502	3663.5	4158.7	9.6138	5212	3663.5	4158.7	9.5888	4952	3663.5	4158.6	9.5652
850	5759.	3758.3	4276.6	9.7212	5455	3758.3	4276.6	9.6962	5183.	3758.3	4276.5	9.6725
900	6015	3854.8	4396.2	9.8253	5698	3854.8	4396.1	9.8004	5414.	3854.8	4396.1	9.7767
950	6272.	3953.0	4517.4	9.9266	5941	3953.0	4517.4	9.9016	5644.	3953.0	4517.4	9.8779
1000	6528.	4052.8	4640.3	10.0251	6184	4052.8	4640.3	10.0001	5875	4052.8	4640.3	9.9764
1100	7041.	4257.3	4891.0	10.2145	6670	4257.3	4891.0	10.1896	6337.	4257.3	4891.0	10.1659
1200	7554.	4467.7	5147.6	10.3949	7156	4467.7	5147.6	10.3699	6799	4467.7	5147.6	10.3463
1300	8067.	4683.5	5409.5	10.5669	7642	4683.5	5409.5	10.5419	7260.	4683.5	5409.5	10.5183

1 Bar = 1.01972 kg/sq cm.; 1 Joule = 1/4.1868 I.T.Cal.

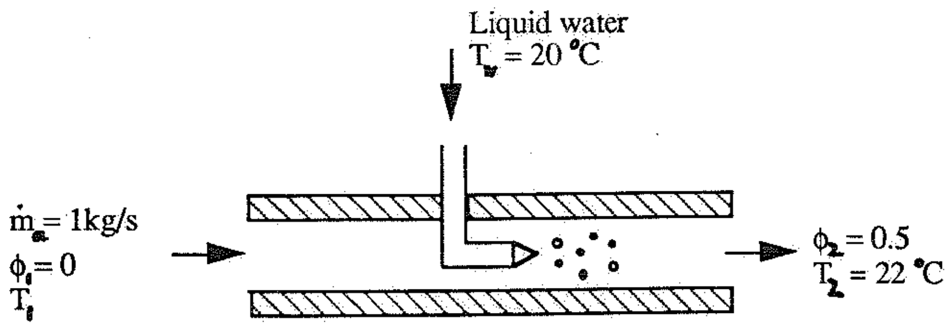
1.1 (102.31) v	u	h	s	1.2 (104.80) v	u	h	s	1.3 (107.13) v	u	h	s	p (t Sat.) t
1549.5	2509.2	2679.7	7.3273	1428.4	2512.1	2683.5	7.2981	1325.4	2514.8	2687.1	7.2713	Sat.
1309.2	2426.4	2570.4	7.0136	1196.0	2424.5	2568.1	6.9678	1100.2	2422.7	2565.7	6.9251	50
1332.9	2434.4	2581.0	7.0464	1218.0	2432.7	2578.9	7.0009	1120.7	2431.0	2576.6	6.9586	55
1336.5	2442.4	2591.7	7.0785	1239.8	2440.8	2589.6	7.0334	1141.1	2439.2	2587.5	6.9915	60
1379.8	2450.5	2602.2	7.1100	1261.4	2448.9	2600.3	7.0653	1161.2	2447.4	2598.3	7.0237	65
1403.0	2458.4	2612.8	7.1410	1282.9	2457.0	2610.9	7.0965	1181.2	2455.5	2609.1	7.0553	70
1426.0	2466.4	2623.3	7.1713	1304.2	2465.0	2621.5	7.1272	1201.1	2463.7	2619.8	7.0862	75
1448.9	2474.3	2633.7	7.2011	1325.3	2473.0	2632.1	7.1572	1220.7	2471.7	2630.4	7.1166	80
1471.7	2482.2	2644.1	7.2303	1346.4	2481.0	2642.5	7.1867	1240.1	2479.8	2641.0	7.1463	85
1494.3	2490.0	2654.4	7.2589	1367.2	2488.9	2653.0	7.2156	1259.2	2487.8	2651.5	7.1754	90
1516.8	2497.9	2664.7	7.2871	1388.0	2496.8	2663.3	7.2440	1279.0	2495.7	2662.0	7.2040	95
1539.2	2505.6	2675.0	7.3147	1408.7	2504.6	2673.7	7.2718	1298.2	2503.6	2672.4	7.2321	100
1583.7	2521.1	2695.3	7.3686	1449.7	2520.2	2694.2	7.3261	1336.3	2519.3	2693.0	7.2867	110
1627.9	2536.5	2715.6	7.4207	1490.4	2535.7	2714.5	7.3785	1374.0	2534.9	2713.5	7.3395	120
1671.7	2551.8	2735.7	7.4713	1530.7	2551.1	2734.8	7.4293	1411.4	2550.3	2733.8	7.3906	130
1715.4	2567.0	2755.7	7.5203	1570.9	2566.4	2754.9	7.4786	1448.6	2565.7	2754.0	7.4401	140
1758.8	2582.2	2775.6	7.5680	1610.8	2581.6	2774.9	7.5265	1485.6	2581.0	2774.3	7.4882	150
1802.0	2597.3	2795.5	7.6145	1650.6	2596.8	2794.9	7.5731	1522.4	2596.3	2794.2	7.5349	160
1845.1	2612.4	2815.4	7.6598	1690.2	2611.9	2814.8	7.6185	1559.1	2611.5	2814.1	7.5805	170
1888.1	2627.5	2835.2	7.7040	1729.7	2627.1	2834.6	7.6629	1595.6	2626.6	2834.1	7.6250	180
1931.0	2642.6	2855.0	7.7472	1769.0	2642.2	2854.5	7.7062	1632.0	2641.8	2854.0	7.6684	190
[illegible]	[illegible]	2874.8	[illegible]	1808.1	2657.3	2874.3	7.7486	1668.3	2657.0	2873.9	7.7109	200
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2672.5	2894.2	7.7901	1704.5	2672.1	2893.7	7.7525	210
[illegible]	[illegible]	[illegible]	[illegible]	1886.6	2687.6	2914.0	7.8308	1740.7	2687.3	2913.6	7.7932	220
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2702.8	2933.9	7.8706	1776.8	2702.5	2933.5	7.8331	230
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2718.0	2953.8	7.9098	1812.9	2717.7	2953.4	7.8723	240
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.9482	1848.9	2733.0	2973.3	7.9108	250
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.9860	1884.8	2748.3	2993.3	7.9486	260
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.0231	1920.7	2763.6	3013.3	7.9857	270
2314	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.0596	1956.6	2779.0	3033.4	8.0223	280
2356	2794.8	3054.0	8.1363	2159	2794.6	3053.7	8.0956	1992.5	2794.4	3053.4	8.0583	290
2398	[illegible]	3074.1	[illegible]	2199	2810.1	3073.8	8.1310	2028	2809.9	3073.6	8.0937	300
2483	2841.3	3114.4	8.2406	2235	2841.1	3114.2	8.2062	[illegible]	2841.0	3113.9	8.1630	320
2567	2872.6	3155.0	8.3079	2353	2872.4	3154.8	8.2635	2171	2872.3	3154.5	8.2303	340
2652.	2904.1	3195.7	8.3733	2430	2903.9	3195.5	8.3330	2243	2903.8	3195.4	8.2958	360
2736	2935.8	3236.7	8.4171	2508	2935.7	3236.6	8.3968	2314	2935.5	3236.4	8.3596	380
2820.	2967.8	3278.0	8.4993	2585	2967.7	3277.8	8.4590	2386.	2967.5	3277.7	8.4219	400
2904	3000.0	3319.5	8.5601	2662	2999.9	3319.3	8.5197	2457.	2999.8	3319.2	8.4827	420
2989.	3032.5	3361.2	8.6194	2739	3032.4	3361.1	8.5791	2528	3032.3	3361.0	8.5421	440
3073.	3065.2	3403.2	8.6775	2816.	3065.1	3403.1	8.6372	2600	3065.0	3403.0	8.6002	460
3157.	3098.2	3445.5	8.7344	2894.	3098.1	3445.4	8.6941	2671.	3098.1	3445.3	8.6571	480
3241.	3131.5	3488.0	8.7901	2971	3131.4	3487.9	8.7498	2742.	3131.3	3487.8	8.7128	500
3325.	3165.0	3530.8	8.8447	3048.	3165.0	3530.7	8.8045	2813.	3164.9	3530.6	8.7675	520
3409.	3198.8	3573.9	8.8983	3125.	3198.8	3573.8	8.8581	2884.	3198.7	3573.7	8.8211	540
3493.	3232.9	3617.2	8.9510	3202	3232.9	3617.1	8.9107	2956.	3232.8	3617.0	8.8737	560
3577.	3267.3	3660.8	9.0027	3279.	3267.2	3660.7	8.9625	3027.	3267.1	3660.6	8.9254	580
3661.	3301.9	3704.6	9.0535	3356	3301.8	3704.6	9.0133	3098.	3301.8	3704.5	8.9763	600
3746.	3336.8	3748.8	9.1035	3433	3336.7	3748.7	9.0633	3169	3336.7	3748.6	9.0263	620
3830.	3371.9	3793.2	9.1527	3510	3371.9	3793.1	9.1125	3240	3371.8	3793.1	9.0755	640
3914.	3407.4	3837.9	9.2011	3587	3407.4	3837.8	9.1609	3311.	3407.3	3837.8	9.1239	660
3998.	3443.1	3882.9	9.2488	3664.	3443.1	3882.8	9.2086	3382.	3443.0	3882.7	9.1716	680
4082.	3479.1	3928.1	9.2957	3741	3479.1	3928.1	9.2555	3453.	3479.1	3928.0	9.2186	700
4292.	3570.4	4042.5	9.4103	3934.	3570.4	4042.4	9.3701	3631	3570.3	4042.4	9.3332	750
4501.	3663.4	4158.6	9.5211	4126.	3663.4	4158.6	9.4810	3809.	3663.4	4158.5	9.4440	800
4711.	3758.2	4276.5	9.6285	4319.	3758.2	4276.5	9.5883	3986.	3758.2	4276.4	9.5514	850
4921.	3854.8	4396.1	9.7327	4511	3854.7	4396.1	9.6925	4164.	3854.7	4396.0	9.6555	900
5131.	3952.9	4517.4	9.8339	4704.	3952.9	4517.3	9.7937	4342.	3952.9	4517.3	9.7568	950
5341.	4052.8	4640.3	9.9324	4896	4052.7	4640.3	9.8922	4519.	4052.7	4640.2	9.8553	1000
5761.	4257.2	4890.9	10.1219	5281	4257.2	4890.9	10.0817	4875	4257.2	4890.9	10.0448	1100
6181.	4467.7	5147.5	10.3023	5666	4467.7	5147.5	10.2621	5230	4467.6	5147.5	10.2251	1200
6600.	4683.5	5409.5	10.4743	6050	4683.4	5409.5	10.4341	5585.	4683.4	5409.4	10.3971	1300

1 Bar = 1.01972 kg/sq.cm.; 1 Joule = 1/4.1868 I.T.Cal.

h = kJ/kg   s = kJ/kg K

Problem 5 (25/135)

The air in Boston is not only very humid in the summer, but also very dry in the winter. Hence, humidifiers are sold, one type of which is depicted in the figure.



Air is entering the well-insulated humidifier at a relative humidity of 0 %. Liquid water at a temperature of 20 °C is added to the air flow. The air leaving the humidifier has a relative humidity of 50 % and a temperature of 22 °C. The streams entering and leaving the humidifier are at a pressure of 1 bar. The air and the water vapor can be modeled as perfect gases. At constant pressure, the specific heat of dry air $c_{p,a} = 1$ kJ/kg K and that of water vapor $c_{p,v} = 1.86$ kJ/kgK. The molecular weights of dry air and water vapor are 29 kg/kmol and 18 kg/kmol, respectively. The liquid water behaves as an incompressible liquid ($dh = c\,dT$) with $c = 4.19$ kJ/kg K. The properties of saturated water are attached.

(10/135) a. What is the liquid water flow rate ?

(15/135) b. What is the temperature of the entering air ?

TABLE B.14. Values of properties of water, H_2O.[a]

Properties of saturated H_2O

T	p	v_f	v_g	u_f	u_{gf}	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
°C	kPa	m³/kg			kJ/kg			kJ/kg			kJ/kg K	
0.01	0.61133	0.0009997	206.14	0.0	2374.9	2374.9	0.0	2500.9	2500.9	0.0	9.1555	9.1555
5	0.87210	0.0009999	147.12	20.4	2361.4	2381.8	20.4	2489.7	2510.1	0.0741	8.9508	9.0249
10	1.2276	0.0010004	106.38	41.1	2347.6	2388.7	41.1	2478.2	2519.3	0.1478	8.7522	8.9000
15	1.7051	0.0010011	77.926	62.0	2333.6	2395.6	62.0	2466.5	2528.5	0.2207	8.5598	8.7806
20	2.3385	0.0010021	57.791	82.9	2319.6	2402.5	82.9	2454.7	2537.6	0.2928	8.3736	8.6664
25	3.1691	0.0010032	43.360	103.9	2305.4	2409.3	103.9	2442.8	2546.7	0.3640	8.1932	8.5571
30	4.2460	0.0010046	32.894	125.0	2291.1	2416.1	125.0	2430.8	2555.8	0.4341	8.0184	8.4525
35	5.6280	0.0010062	25.216	146.1	2276.8	2422.9	146.1	2418.7	2564.8	0.5032	7.8491	8.3523
40	7.3836	0.0010080	19.523	167.3	2262.4	2429.7	167.3	2406.6	2573.8	0.5712	7.6850	8.2562
45	9.5932	0.0010100	15.258	188.4	2248.0	2436.4	188.4	2394.4	2582.7	0.6381	7.5259	8.1640
50	12.349	0.0010121	12.032	209.5	2233.5	2443.0	209.5	2382.1	2591.6	0.7039	7.3716	8.0755
60	19.940	0.0010170	7.6710	251.6	2204.6	2456.2	251.6	2357.5	2609.1	0.8323	7.0764	7.9088
70	31.188	0.0010227	5.0422	293.7	2175.4	2469.1	293.7	2332.7	2626.4	0.9567	6.7978	7.7545
80	47.389	0.0010289	3.4072	335.6	2146.1	2481.7	335.7	2307.5	2643.2	1.0772	6.5342	7.6114
90	70.138	0.0010359	2.3606	377.5	2116.6	2494.1	377.6	2282.1	2659.6	1.1942	6.2841	7.4782
100	101.35	0.0010434	1.6729	419.4	2086.6	2506.1	419.5	2256.1	2675.6	1.3080	6.0460	7.3540
110	143.27	0.0010516	1.2102	461.4	2056.3	2517.6	461.5	2229.5	2691.0	1.4189	5.8189	7.2379
120	198.53	0.0010604	0.89186	503.5	2025.3	2528.8	503.7	2202.1	2705.8	1.5275	5.6013	7.1288
130	270.09	0.0010699	0.66851	545.8	1993.6	2539.4	546.1	2173.9	2720.0	1.6338	5.3923	7.0261
140	361.29	0.0010800	0.50885	588.4	1961.2	2549.6	588.8	2144.6	2733.4	1.7381	5.1910	6.9291
150	475.84	0.0010907	0.39278	631.2	1927.8	2559.1	631.8	2114.2	2746.0	1.8406	4.9964	6.8370
160	617.82	0.0011022	0.30706	674.4	1893.5	2567.9	675.1	2082.5	2757.6	1.9415	4.8079	6.7493
170	791.66	0.0011144	0.24282	718.0	1858.0	2576.0	718.8	2049.4	2768.2	2.0409	4.6246	6.6655
180	1002.1	0.0011275	0.19404	761.8	1821.4	2583.2	763.0	2014.7	2777.7	2.1388	4.4461	6.5849
190	1254.4	0.0011414	0.15653	806.1	1783.5	2589.5	807.5	1978.4	2785.9	2.2354	4.2716	6.5070
200	1553.8	0.0011564	0.12735	850.7	1744.1	2594.8	852.5	1940.2	2792.7	2.3308	4.1006	6.4314
210	1906.2	0.0011724	0.10441	895.7	1703.3	2599.0	897.9	1900.1	2798.0	2.4249	3.9326	6.3576
220	2317.8	0.0011897	0.086186	941.1	1660.7	2601.9	943.9	1857.7	2801.6	2.5181	3.7671	6.2852
230	2794.8	0.0012084	0.071577	987.1	1616.3	2603.4	990.4	1813.0	2803.4	2.6104	3.6033	6.2137
240	3344.2	0.0012287	0.059760	1033.5	1569.9	2603.4	1037.7	1765.6	2803.3	2.7020	3.4408	6.1428
250	3972.9	0.0012509	0.050123	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7932	3.2788	6.0720
260	4688.5	0.0012753	0.042202	1128.7	1469.8	2598.5	1134.7	1661.6	2796.3	2.8843	3.1167	6.0009
270	5498.6	0.0013023	0.035641	1177.7	1415.4	2593.1	1184.8	1604.3	2789.1	2.9755	2.9536	5.9291
280	6411.6	0.0013323	0.030168	1227.8	1357.7	2585.5	1236.3	1542.6	2778.9	3.0672	2.7888	5.8560
290	7435.9	0.0013659	0.025568	1279.3	1296.1	2575.4	1289.4	1476.1	2765.5	3.1599	2.6212	5.7811
300	8580.9	0.0014040	0.021673	1332.3	1230.0	2562.4	1344.4	1403.9	2748.3	3.2539	2.4495	5.7034
310	9856.4	0.0014479	0.018349	1387.3	1158.5	2545.8	1401.6	1325.0	2726.6	3.3496	2.2722	5.6219
320	11274	0.0014991	0.015486	1444.6	1080.3	2524.9	1461.5	1237.9	2699.4	3.4479	2.0871	5.5350
330	12845	0.0015606	0.012996	1504.9	993.4	2498.3	1524.9	1140.3	2665.2	3.5499	1.8906	5.4405
340	14586	0.0016373	0.010797	1569.3	894.6	2463.9	1593.2	1028.2	2621.4	3.6576	1.6769	5.3345
350	16513	0.0017396	0.0088132	1640.5	777.2	2417.8	1669.3	894.0	2563.3	3.7754	1.4347	5.2101
360	18651	0.0018942	0.0069457	1725.0	625.9	2350.9	1760.4	720.1	2480.4	3.9142	1.1373	5.0515
370	21027	0.0022178	0.0049282	1847.9	380.3	2228.1	1894.5	437.2	2331.7	4.1167	0.6798	4.7965
374.14	22089	0.0031550	0.0031550	2029.1	0.0	2029.1	2098.8	0.0	2098.8	4.4289	0.0000	4.4289

[a] Data generated using the correlations in W. C. Reynolds, *Thermodynamic Properties in SI*, Dept. of Mech. Eng. Stanford University, Stanford, CA, 1979.

12/17/90

2.451J and 22.571J

Solution Final Examination

Problem 1

a. Any two states of a system may always be the end states of a weight process, that is, the initial and final states of a change of state that involves no net effects external to the system except the change in elevation between z_1 and z_2 of a weight. Moreover, for a given weight, the value of the quantity $Mg(z_1 - z_2)$ is fixed by the end states of the system, and independent of the details of the weight process where M is the mass of the weight and g the gravitational acceleration.

b. Among all the states of a system with a given value of the energy, and given values of the amounts of constituents and the parameters, there exists one and only one stable equilibrium state. Moreover, starting from any state of a system it is always possible to reach a stable equilibrium state with arbitrarily specified values of amounts of constituents and parameters by means of a reversible weight process.

Problem 2

a. $$W_{eq} = \left(1 - \frac{T_o}{T_1}\right) Q^{R_1 \rightarrow} = \left(1 - \frac{300}{1000}\right) \times 7000 = 4900 \text{ kJ.}$$

b. The energy into reservoir R_2 is given by

$$Q^{R_2 \leftarrow} = T_2 S^{R_2 \leftarrow} = 500 \times 4 = 2000 \text{ kJ}$$

The entropy into the environment is given by

$$S^{e \leftarrow} = \frac{Q^{R_1 \rightarrow}}{T_1} - \frac{Q^{R_2 \leftarrow}}{T_2} + (S_{irr})_s + (S_{irr})_e$$

$$= 7 - 4 + 7 + 2 = 12 \text{ kJ/K}$$

It follows that the energy into the environment

$$Q^{e \leftarrow} = T_o S^{e \leftarrow} = 300 \times 12 = 3600 \text{ kJ}$$

and so the energy balance for the engine yields

$$W_S^{\rightarrow} = Q^{R_1 \rightarrow} - Q^{R_2 \leftarrow} - Q^{e \leftarrow} = 7000 - 2000 - 3600$$

$$= \underline{1400 \text{ kJ}}$$

c. The work equivalent of the heat into R_2 is

$$W^{R_2 \leftarrow} = \left(1 - \frac{T_o}{T_2}\right) \times Q^{R_2 \leftarrow} = \left(1 - \frac{300}{500}\right) \times 2000 = 800 \text{ kJ}$$

So the effectiveness is

$$\epsilon = (1400 + 800)/4900 = \underline{44.9\%}$$

Solution Problem 3

a. $\dot{Q}^{\leftarrow} = \dot{m}(h_2 - h_1) = 100 \frac{kg}{s}(3273.6 - 433.6)\frac{kJ}{kg}$

$h_2 = 3237.6$ kJ/kg

$h_1 = 433.6$ kJ/kg

$\dot{Q}^{\leftarrow} = 280.4$ MW ✗

b. Entropy balance $0 = \dot{m}(s_1 - s_2) + \frac{\dot{Q}^{\leftarrow}}{T_Q} + \dot{S}_{irr}$

$\dot{S}_{irr} = \dot{m}(s_2 - s_1) - \frac{\dot{Q}^{\leftarrow}}{T_Q} = 264.6 \frac{kW}{K}$

$s_2 = 6.1391$ kJ/kg K

$s_1 = 1.2903$ kJ/kg K

Lost work rate $\Delta\dot{W}^{\rightarrow} = T_0 \dot{S}_{irr} = 78.84$ MW

c. Change in availability rate $= \dot{m}\,\Delta(h - T_0 s)$

$= 135.9$ MW ✓

Problem 4

a. The energy balance for the heat exchanger yields

$$c_p (T_{g1} - T_{g2}) = m_w (h_{w2} - h_{w1})$$

For liquid water at $T_{w1} = 20°C$ and $p_{w1} = 1$ bar

$$h_{w1} = 83.95 + (86.30 - 83.95)/25 = \sout{86.4}\ 84.04 \text{ kJ/kg}$$

$$s_{w1} \cong 0.2966 \text{ kJ/kg K}$$

For steam at 420°C and 1 bar

$$h_{w2} = 3319.6 \text{ kJ/kg}$$

$$s_{w2} = 8.6042 \text{ kJ/kg K}$$

So

$$m_w = 1 \times (750 - 310)/(3319.6 - 86.4) = \underline{0.136} \ \frac{\text{kg steam}}{\text{kg gas}}$$

b. The change in availability of the gas is

$$\overrightarrow{W}_{largest} = c_p (T_{g1} - T_{g2}) - T_0 \left[c_p \ln \frac{T_{g1}}{T_{g2}} - R_m \ln \frac{p_{g1}}{p_{g2}} \right]$$

$$= 440 - 293 \left[\ln \frac{750}{310} - 0.286 \ln 60 \right]$$

$$= \underline{524.38} \text{ kJ/kg gas.}$$

The change in availability of the water

$$-\overleftarrow{W}_{least} = m_w \left[h_{w2} - h_{w1} - T_0 (s_{w2} - s_{w1}) \right] = \underline{122.27} \text{ kJ/kg gas}$$

So $\overrightarrow{W} = 524.38 - 122.27 = \underline{402.11}$ kJ/kg gas

c. $\dot{S}_{irr} = \overrightarrow{W} / T_0 = 402.11 / 293 = \underline{1.37} \frac{kJ}{K \text{ kg gas}}$

d. $\epsilon = 122.27 / 524.38 = \underline{23.3\%}$

Solution Problem 5

a. Mass balance $\dot{m}_w = \dot{m}_a \omega_2$

$$\omega = 0.622 \frac{\phi}{p/p_{sat}(T) - \phi}$$

$p = 1$ bar ; $p_{sat}(T = 22°C) = 2.6707$ kPa

$\omega_2 = 0.008418 \longrightarrow \dot{m}_w = 8.418$ g/s

b. Energy balance $\dot{m}_a h_{a,1} + \dot{m}_w h_w = \dot{m}_a (h_{a,2} + \omega_2 h_{v,2})$

If the enthalpy of liquid water at 0°C is set equal to zero, then $h_w = c\, T_w$

$h_{v,2} = h_{fg}(T = 0°C) + c_{p,v} T_2$

$h_{a,1} = c_{p,a} T_1$; $h_{a,2} = c_{p,a} T_2$

$$T_1 = T_2 + \frac{\omega_2}{c_{p,a}} \left(h_{fg}(T = 0°C) + c_{p,v} T_2 - c\, T_w \right)$$

$T_1 = 42.03$ °C

Problem 1

An amount of 4×10^{-7} kmol of helium gas is enclosed in the cylinder shown in the figure. The massless piston can move without friction in the cylinder between elevations $H_L = 0.05$ m and $H_H = 0.5$ m. Piston and cylinder are well insulated. The gas in the cylinder can be heated by an electric heater, and it can be stirred by a paddle wheel. The mass of the weight is $M_W = 1$ kg, and the piston diameter $D = 0.1$ m. Vacuum prevails on the outside of the cylinder.

(a) Define carefully a system A whose only constituent is the helium gas.

(b) In state 1, the piston is at a position H_1 with $H_L < H_1 < H_H$ and is at rest. What kind of state is state 1?

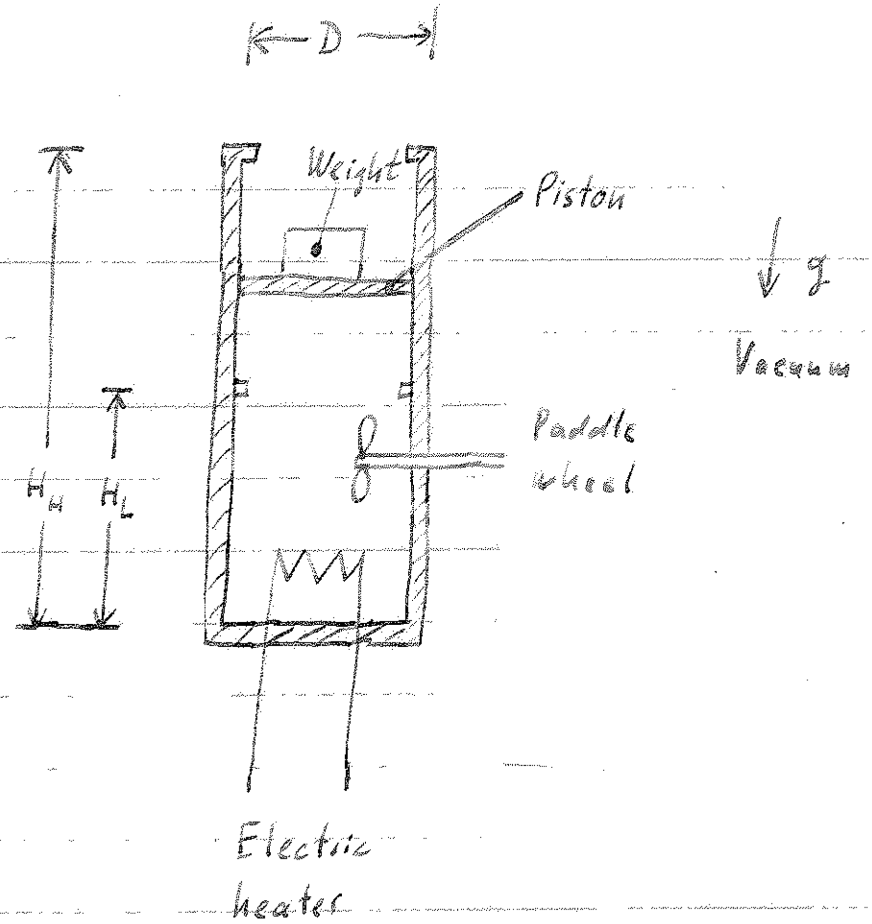
(c) State 2 of system A is reached from state 1 by supplying an energy of 1.16 J to the gas through the electric heater, with $H_L < H_2 < H_H$. Is the process $1 \to 2$ a weight process?

(d) State 3 of system A is reached from state 1 by supplying an energy of 1.16 J to the gas through the paddle wheel, with $H_3 = H_2$. Are states 2 and 3 identical?

(e) Is the process 1 → 3 a weight process?

(f) If $H_2 - H_1 = 0.0474$ m, what is the difference in the energies of system A in states 1 and 2, $E_2^A - E_1^A$?

(g) System A is modified such that the piston can be pinned in place at any position. In state 3 the piston is pinned in place. Energy is delivered to system A in the amount of 5 J through the paddle wheel to bring the system in state 4. For the composite system consisting of system A, the piston and the weight, what kind of state is state 4? Explain your answer.


D
Weight
Piston
g
Vacuum
Paddle wheel
H_u
H_L
Electric heater