THERMODYNAMICS – Final Exam

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Date: Wednesday, February 3rd 2010; 01:00PM
Location: ENG 406
Instructor: Dr. Wassim HABCHI
Notes: No documents allowed
Value: 40% of Total Grade
Time: 120 Minutes

[____ / 100]

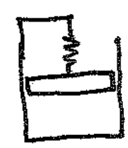
Problem I (30 points)

A piston-cylinder device contains 2kg of water. The piston is connected to a spring of stiffness 10 kN/m that is initially at rest. The mass of the piston is 50kg and it has a surface area of 1000cm^2. Initially 10% of the water is in the vapor phase while the rest is in the liquid phase. Now heat is added to the system until its volume has doubled. If the atmospheric pressure P_{atm}=120kPa, and the gravitational acceleration g=10m/s^2, determine:

a) The final pressure inside the cylinder

b) The boundary work associated to this process.

c) The amount of heat transferred to the water.



Solution:

a) *Initial State: Equilibrium of force: $P_1 \times A = mg + P_{at} \times A$

$P_1 = \frac{mg}{A} + P_{at}$

$P_1 = \frac{50 \times 10}{1000 \times 10^{-4}} \times 10^{-3} + 120 = \boxed{125 k}$

And $x_1 = 0,1$ → $v_1 = v_f + x_1 v_{fg} = 0,001048 + 0,1(1,3750 - 0,001048)$

Table A-5

$v_1 = 0,1384\ m^3/Kg$ → $V_1 = m \times v_1 = 2 \times 0,1384 = 0,2768\ m^3$

*Final State: $V_2 = 2V_1 \Rightarrow \Delta V = V_2 - V_1 = 2V_1 - V_1 = V_1 = 0,2768\ m^3$

⇒ the spring is compressed by $\Delta x = \frac{\Delta V}{A} = \frac{0,2768}{1000 \times 10^{-4}} = \boxed{2,768 m}$

And the spring force $F_s = K \Delta x = 10 \times 2,768 = 27,68\ KN$

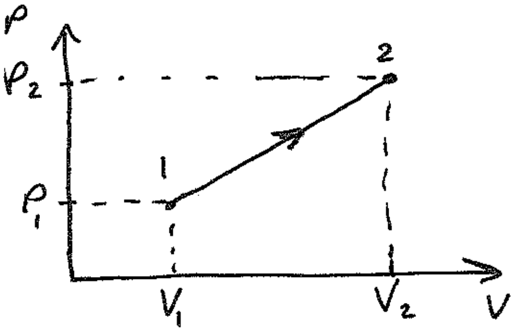
⇒ The pressure induced by the spring is: $P_s = \frac{F_s}{A} = \frac{27,68}{1000 \times 10^{-4}} =$

⇒ $\boxed{P_s = 276,8\ KPa}$

the final pressure within the cylinder is:

$$P_2 = P_s + P_{atm} + \frac{mg}{A} = 276,8 + 120 + 5 = \boxed{401,8\ KPa}$$

b) because of the spring, the pressure rise within the cylinder is linear with respect to V:



$$\Rightarrow W_b = \int_1^2 P\,dV = \frac{1}{2}(V_2 - V_1)(P_1 + P_2) = \frac{1}{2}(0,2768)(125 + 401,8)$$

$$\Rightarrow \boxed{W_b = 72,91\ KJ}$$

c) 1st Law of thermodynamics applied to the cylinder gases:

$$E_{in} - E_{out} = \Delta E_{sys}$$ <u>Assumption</u> $ke \simeq 0$, $pe \simeq 0$

$$Q_{in} - Q_{out}^{\,0} + W_{in}^{\,0} - W_{out}^{\,0} - W_b = \Delta U = m(u_2 - u_1)$$

$$\boxed{Q_{in} = m(u_2 - u_1) + W_b}$$

<u>@ 1</u>: $u_1 = u_f + x_1 u_{fg} = 444,23 + 0,1 \times 2068,8 = 651,11\ KJ/Kg$

<u>@ 2</u>: $P_2 = 401,8\ KPa \simeq 400\ KPa$, $v_2 = 0,2768\ m^3/Kg$ $\xrightarrow{\boxed{A-5}}$ $v_f < v_2 < v_g \Rightarrow$ Sat. Liq. vap. mixture

And $x_2 = \dfrac{v_2 - v_f}{v_g - v_f} = \dfrac{0,2768 - 0,001084}{0,46242 - 0,001084} = 0,59$

$$\Rightarrow u_2 = u_f + x_2 u_{fg} = 604,22 + 0,598 \times (1948,9) = 1769,66\ KJ/Kg$$

$$\Rightarrow Q_{in} = 2 \times (1769,66 - 651,11) + 72,91 = \boxed{2310,01\ KJ}$$

Problem III (35 points)

A heat pump is to be used for heating a house during winter. The house is to be maintained at a temperature of 23°C at all times. When the outside temperature drops to -3°C, the heat losses from the house are estimated to be 60 000 KJ/h.

a) Show that for a reversible heat pump operating between two energy reservoirs at temperatures T_L and T_H, the coefficient of performance is defined as:

$$COP_{HP,rev} = \frac{1}{1 - \frac{T_L}{T_H}}$$

b) Determine the minimum electric power (in KJ / h) required to run the compressor of the heat pump described above if heat is extracted from:
   Case 1: The outside air at -3°C.
   Case 2: A nearby river at 10°C.

c) The previous house is in a country where the cost of electricity is 0.25 $ / MJ. If the heat pump is operational for 18 h / day, determine the minimum daily cost of the system for both **Case 1** and **Case 2**.

d) What would the cost become if an electric resistance is used instead of the heat pump?

e) If this heat pump was reversible, what would be ~~the power needed to drive the compressor $\dot{W}_{in}$ and~~ the amount of heat extracted from the external source Q_L? for both case

Solution:

a) Applying the 1st Law of thermodynamics to a heat pump gives:

$\dot{W}_{in} + \dot{Q}_L = \dot{Q}_H$

However the efficiency of a heat pump is defined as:

$$\eta_{HP} = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_L} = \frac{1}{1 - \frac{\dot{Q}_L}{\dot{Q}_H}}$$

However, for a reversible heat pump, we know that: $\frac{\dot{Q}_L}{\dot{Q}_H} = \frac{T_L}{T_H}$

$$\Rightarrow \boxed{\eta_{HP,rev} = \frac{1}{1 - \frac{T_L}{T_H}}}$$

b) The minimum power required by the compressor would be obtained if the heat pump was reversible.

But $COP_{HP,rev} = \frac{1}{1 - \frac{T_L}{T_H}}$ with $T_H = 23°C = 296K$

* Case 1: $T_L = -3°C = 270\,K \rightarrow COP_{HP,rev(1)} = \frac{1}{1 - \frac{270}{296}} = 11,385$

However: $COP_{HP,rev(1)} = \frac{\dot{Q}_H}{\dot{W}_{in,min(1)}} \rightarrow \dot{W}_{in,min(1)} = \frac{\dot{Q}_H}{COP_{HP,rev(1)}} = \frac{60000}{11,385} = \boxed{5270 \text{ kJ/h}}$

* Case 2: $T_L = 10°C = 283K \longrightarrow COP_{HP,rev(2)} = \frac{1}{1 - \frac{283}{296}} = 22,77$

And $\dot{W}_{in,min(2)} = \frac{\dot{Q}_H}{COP_{HP,rev(2)}} = \frac{60000}{22,77} = \boxed{2635 \text{ kJ/h}}$

c) Case 1: $Cost = 18 \times 5270 \times 10^{-3} \times 0,25 = \boxed{23,715 \text{ \$/Day}}$

Case 2: $Cost = 18 \times 2635 \times 10^{-3} \times 0,25 = \boxed{11,871 \text{ \$/Day}}$

d) If an electric resistance is used, 60000 kJ/h of electricity would have to be provided to run it $\Longrightarrow$

$Cost = 60000 \times 18 \times 10^{-3} \times 0,25 = \boxed{270 \text{ \$/Day}}$

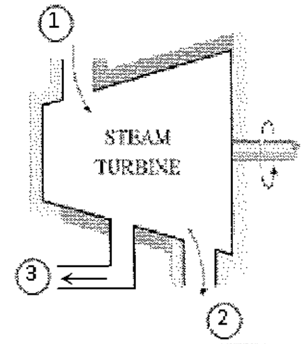
e) $\dot{Q}_L = \dot{Q}_H - \dot{W}_{in}$

* Case 1: $\dot{Q}_{L_1} = 60000 - 5270 = \boxed{54730 \text{ kJ/h}}$

* Case 2: $\dot{Q}_{L_2} = 60000 - 2635 = \boxed{57365 \text{ kJ/h}}$

Problem III (30 points)

Steam enters an adiabatic turbine steadily at P_1=10MPa, T_1=700°C, V_1=30m/s and leaves as a saturated vapor at P_2=200 KPa with a velocity V_2=195m/s. Part of the steam is removed at an intermediate stage of the turbine at P_3=4MPa, T_3=500°C, V_3=50m/s with a mass flow rate $\dot{m}_3 = 2\,kg/s$. The latter is to be used for heating purposes. If the power output of this turbine is 5MW, determine:



a) The mass flow rate of steam entering the turbine $\dot{m}_1$ (**10 points**)

b) The isentropic efficiency of the turbine (**10 points**)

c) The rate of entropy generation $\dot{S}_{gen}$ of the turbine (**10 points**)

Solution:

a) Mass balance: $\boxed{\dot{m}_1 = \dot{m}_2 + \dot{m}_3}$

@1: $P_1 = 10\,MPa$, $T_1 = 700°C$ $\xrightarrow{A-6}$ $h_1 = 3870\ KJ/Kg$, $s_1 = 7{,}1693\ KJ/Kg.K$

@2: $P_2 = 200\,KPa$, $x = 1$ $\xrightarrow{A-5}$ $h_2 = h_g = 2706{,}3\,KJ/Kg$, $s_2 = s_g = 7{,}1270\,KJ/Kg.K$

@3: $P_3 = 4\,MPa$, $T_3 = 500°C$ $\xrightarrow{A-6}$ $h_3 = 3446\ KJ/Kg$, $s_3 = 7{,}0922\,KJ/Kg.K$

Energy balance: $\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{sys}}{dt} \to 0$ (Steady-flow device)

$$(\dot{Q}_{in} - \dot{Q}_{out}) + (\dot{W}_{in} - \dot{W}_{out}) + (\dot{E}_{mass,in} - \dot{E}_{mass,out}) = 0$$

$$-\dot{W} + \dot{m}_1\left(h_1 + \frac{V_1^2}{2}\right) - \dot{m}_2\left(h_2 + \frac{V_2^2}{2}\right) - \dot{m}_3\left(h_3 + \frac{V_3^2}{2}\right) = 0$$

$$\dot{W} = \dot{m}_1\left(h_1 + \frac{V_1^2}{2}\right) - (\dot{m}_1 - \dot{m}_3)\left(h_2 + \frac{V_2^2}{2}\right) - \dot{m}_3\left(h_3 + \frac{V_3^2}{2}\right) = 0$$

$$\Rightarrow \dot{m}_1 = \frac{\dot{W} - \dot{m}_3\left[\left(h_2 + \frac{V_2^2}{2}\right) - \left(h_3 + V_3^2/2\right)\right]}{\left(h_1 + \frac{V_1^2}{2}\right) - \left(h_2 + \frac{V_2^2}{2}\right)}$$

$$\Rightarrow \dot{m}_1 = \frac{5000 - 2\left[\left(2706,3 + \frac{195^2}{2}\times 10^{-3}\right) - \left(3446 + \frac{50^2}{2}\times 10^{-3}\right)\right]}{\left(3870 + \frac{30^2}{2}\times 10^{-3}\right) - \left(2706,3 + \frac{195^2}{2}\times 10^{-3}\right)}$$

$$\Rightarrow \dot{m}_1 = \frac{6443,875}{1145,1375} = \boxed{5,63\,Kg/s}$$

b) $\eta_T = ?$

$\eta_T = \frac{\dot{W}_a}{\dot{W}_s}$ but $\dot{W}_a = 5MW$

And $\dot{W}_s = \dot{m}_1\left(h_1 + \frac{V_1^2}{2}\right) - (\dot{m}_1 - \dot{m}_3)\left(h_{2s} + \frac{V_2^2}{2}\right) - \dot{m}_3\left(h_{3s} + \frac{V_3^2}{2}\right)$

@2s: $P_{2s} = P_2 = 200\,KPa$
$s_{2s} = s_1 = 7,1693\,KJ/Kg.K > s_g$
→ superheated vapor

$\xrightarrow{A-6} \frac{h_{2s} - 2706,3}{2769,1 - 2706,3} = \frac{7,1693 - 7,1270}{7,2810 - 7,1270}$

$\Rightarrow \boxed{h_{2s} = 2723,55\,KJ/Kg.}$

@3s: $P_{3s} = P_3 = 4MPa$
$s_{3s} = s_1 = 7,1693\,KJ/Kg.K > s_g$
→ superheated vapor

$\xrightarrow{A-6} \frac{h_{3s} - 3446}{3674,9 - 3446} = \frac{7,1693 - 7,0922}{7,3706 - 7,0922}$

$\Rightarrow \boxed{h_{3s} = 3509,39\,KJ/Kg}$

$\Rightarrow \dot{W}_s = 5,63\left(3870 + \frac{30^2}{2}\times 10^{-3}\right) - 3,63\left(2723,55 + \frac{195^2}{2}\times 10^{-3}\right) - 2\left(3509,39 + \frac{50^2}{2}\times 10^{-3}\right)$

$\dot{W}_s = 4813,85\ KW = 4,814\ MW$

$\Rightarrow \eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{5}{4,814} = 1,038 > 1$ (Impossible, this turbine doesn't exist)

c) Entropy balance:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \frac{dS_{sys}}{dt}^{\nearrow 0} = 0$$

$\dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{m}_3 s_3 + \dot{S}_{gen} = 0$

$\Rightarrow \dot{S}_{gen} = -\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{m}_3 s_3 = -5,63\times 7,1693 + 3,63\times 7,1270 + 2\times 7,0922$

$\Rightarrow \dot{S}_{gen} = -0,307749\,KW/K < 0 \Rightarrow$ It is impossible to operate this turbine under the given conditions.

TABLE A–5

Saturated water—Pressure table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
550	155.46	0.001097	0.34261	655.16	1908.8	2563.9	655.77	2096.6	2752.4	1.8970	4.8916	6.7886
600	158.83	0.001101	0.31560	669.72	1897.1	2566.8	670.38	2085.8	2756.2	1.9308	4.8285	6.7593
650	161.98	0.001104	0.29260	683.37	1886.1	2569.4	684.08	2075.5	2759.6	1.9623	4.7699	6.7322
700	164.95	0.001108	0.27278	696.23	1875.6	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
750	167.75	0.001111	0.25552	708.40	1865.6	2574.0	709.24	2056.4	2765.7	2.0195	4.6642	6.6837

TABLE A–5

Saturated water—Pressure table (*Continued*)

		Specific volume, m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
800	170.41	0.001115	0.24035	719.97	1856.1	2576.0	720.87	2047.5	2768.3	2.0457	4.6160	6.6616
850	172.94	0.001118	0.22690	731.00	1846.9	2577.9	731.95	2038.8	2770.8	2.0705	4.5705	6.6409
900	175.35	0.001121	0.21489	741.55	1838.1	2579.6	742.56	2030.5	2773.0	2.0941	4.5273	6.6213
950	177.66	0.001124	0.20411	751.67	1829.6	2581.3	752.74	2022.4	2775.2	2.1166	4.4862	6.6027
1000	179.88	0.001127	0.19436	761.39	1821.4	2582.8	762.51	2014.6	2777.1	2.1381	4.4470	6.5850
1100	184.06	0.001133	0.17745	779.78	1805.7	2585.5	781.03	1999.6	2780.7	2.1785	4.3735	6.5520
1200	187.96	0.001138	0.16326	796.96	1790.9	2587.8	798.33	1985.4	2783.8	2.2159	4.3058	6.5217
1300	191.60	0.001144	0.15119	813.10	1776.8	2589.9	814.59	1971.9	2786.5	2.2508	4.2428	6.4936
1400	195.04	0.001149	0.14078	828.35	1763.4	2591.8	829.96	1958.9	2788.9	2.2835	4.1840	6.4675
1500	198.29	0.001154	0.13171	842.82	1750.6	2593.4	844.55	1946.4	2791.0	2.3143	4.1287	6.4430
1750	205.72	0.001166	0.11344	876.12	1720.6	2596.7	878.16	1917.1	2795.2	2.3844	4.0033	6.3877
2000	212.38	0.001177	0.099587	906.12	1693.0	2599.1	908.47	1889.8	2798.3	2.4467	3.8923	6.3390
2250	218.41	0.001187	0.088717	933.54	1667.3	2600.9	936.21	1864.3	2800.5	2.5029	3.7926	6.2954
2500	223.95	0.001197	0.079952	958.87	1643.2	2602.1	961.87	1840.1	2801.9	2.5542	3.7016	6.2558
3000	233.85	0.001217	0.066667	1004.6	1598.5	2603.2	1008.3	1794.9	2803.2	2.6454	3.5402	6.1856
3500	242.56	0.001235	0.057061	1045.4	1557.6	2603.0	1049.7	1753.0	2802.7	2.7253	3.3991	6.1244
4000	250.35	0.001252	0.049779	1082.4	1519.3	2601.7	1087.4	1713.5	2800.8	2.7966	3.2731	6.0696
5000	263.94	0.001286	0.039448	1148.1	1448.9	2597.0	1154.5	1639.7	2794.2	2.9207	3.0530	5.9737
6000	275.59	0.001319	0.032449	1205.8	1384.1	2589.9	1213.8	1570.9	2784.6	3.0275	2.8627	5.8902
7000	285.83	0.001352	0.027378	1258.0	1323.0	2581.0	1267.5	1505.2	2772.6	3.1220	2.6927	5.8148
8000	295.01	0.001384	0.023525	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2077	2.5373	5.7450
9000	303.35	0.001418	0.020489	1350.9	1207.6	2558.5	1363.7	1379.3	2742.9	3.2866	2.3925	5.6791
10,000	311.00	0.001452	0.018028	1393.3	1151.8	2545.2	1407.8	1317.6	2725.5	3.3603	2.2556	5.6159
11,000	318.08	0.001488	0.015988	1433.9	1096.6	2530.4	1450.2	1256.1	2706.3	3.4299	2.1245	5.5544
12,000	324.68	0.001526	0.014264	1473.0	1041.3	2514.3	1491.3	1194.1	2685.4	3.4964	1.9975	5.4939
13,000	330.85	0.001566	0.012781	1511.0	985.5	2496.6	1531.4	1131.3	2662.7	3.5606	1.8730	5.4336
14,000	336.67	0.001610	0.011487	1548.4	928.7	2477.1	1571.0	1067.0	2637.9	3.6232	1.7497	5.3728
15,000	342.16	0.001657	0.010341	1585.5	870.3	2455.7	1610.3	1000.5	2610.8	3.6848	1.6261	5.3108
16,000	347.36	0.001710	0.009312	1622.6	809.4	2432.0	1649.9	931.1	2581.0	3.7461	1.5005	5.2466
17,000	352.29	0.001770	0.008374	1660.2	745.1	2405.4	1690.3	857.4	2547.7	3.8082	1.3709	5.1791
18,000	356.99	0.001840	0.007504	1699.1	675.9	2375.0	1732.2	777.8	2510.0	3.8720	1.2343	5.1064
19,000	361.47	0.001926	0.006677	1740.3	598.9	2339.2	1776.8	689.2	2466.0	3.9396	1.0860	5.0256
20,000	365.75	0.002038	0.005862	1785.8	509.0	2294.8	1826.6	585.5	2412.1	4.0146	0.9164	4.9310
21,000	369.83	0.002207	0.004994	1841.6	391.9	2233.5	1888.0	450.4	2338.4	4.1071	0.7005	4.8076
22,000	373.71	0.002703	0.003644	1951.7	140.8	2092.4	2011.1	161.5	2172.6	4.2942	0.2496	4.5439
22,064	373.95	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

TABLE A–6

Superheated water

T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 0.01 MPa (45.81°C)*				*P* = 0.05 MPa (81.32°C)				*P* = 0.10 MPa (99.61°C)			
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941	2505.6	2675.0	7.3589
50	14.867	2443.3	2592.0	8.1741								
100	17.196	2515.5	2687.5	8.4489	3.4187	2511.5	2682.4	7.6953	1.6959	2506.2	2675.8	7.3611
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367	2582.9	2776.6	7.6148
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724	2658.2	2875.5	7.8356
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062	2733.9	2974.5	8.0346
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389	2810.7	3074.5	8.2172
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027	2968.3	3278.6	8.5452
500	35.680	3132.9	3489.7	9.8998	7.1338	3132.6	3489.3	9.1566	3.5655	3132.2	3488.7	8.8362
600	40.296	3303.3	3706.3	10.1631	8.0577	3303.1	3706.0	9.4201	4.0279	3302.8	3705.6	9.0999
700	44.911	3480.8	3929.9	10.4056	8.9813	3480.6	3929.7	9.6626	4.4900	3480.4	3929.4	9.3424
800	49.527	3665.4	4160.6	10.6312	9.9047	3665.2	4160.4	9.8883	4.9519	3665.0	4160.2	9.5682
900	54.143	3856.9	4398.3	10.8429	10.8280	3856.8	4398.2	10.1000	5.4137	3856.7	4398.0	9.7800
1000	58.758	4055.3	4642.8	11.0429	11.7513	4055.2	4642.7	10.3000	5.8755	4055.0	4642.6	9.9800
1100	63.373	4260.0	4893.8	11.2326	12.6745	4259.9	4893.7	10.4897	6.3372	4259.8	4893.6	10.1698
1200	67.989	4470.9	5150.8	11.4132	13.5977	4470.8	5150.7	10.6704	6.7988	4470.7	5150.6	10.3504
1300	72.604	4687.4	5413.4	11.5857	14.5209	4687.3	5413.3	10.8429	7.2605	4687.2	5413.3	10.5229
	P = 0.20 MPa (120.21°C)				*P* = 0.30 MPa (133.52°C)				*P* = 0.40 MPa (143.61°C)			
Sat.	0.88578	2529.1	2706.3	7.1270	0.60582	2543.2	2724.9	6.9917	0.46242	2553.1	2738.1	6.8955
150	0.95986	2577.1	2769.1	7.2810	0.63402	2571.0	2761.2	7.0792	0.47088	2564.4	2752.8	6.9306
200	1.08049	2654.6	2870.7	7.5081	0.71643	2651.0	2865.9	7.3132	0.53434	2647.2	2860.9	7.1723
250	1.19890	2731.4	2971.2	7.7100	0.79645	2728.9	2967.9	7.5180	0.59520	2726.4	2964.5	7.3804
300	1.31623	2808.8	3072.1	7.8941	0.87535	2807.0	3069.6	7.7037	0.65489	2805.1	3067.1	7.5677
400	1.54934	2967.2	3277.0	8.2236	1.03155	2966.0	3275.5	8.0347	0.77265	2964.9	3273.9	7.9003
500	1.78142	3131.4	3487.7	8.5153	1.18672	3130.6	3486.6	8.3271	0.88936	3129.8	3485.5	8.1933
600	2.01302	3302.2	3704.8	8.7793	1.34139	3301.6	3704.0	8.5915	1.00558	3301.0	3703.3	8.4580
700	2.24434	3479.9	3928.8	9.0221	1.49580	3479.5	3928.2	8.8345	1.12152	3479.0	3927.6	8.7012
800	2.47550	3664.7	4159.8	9.2479	1.65004	3664.3	4159.3	9.0605	1.23730	3663.9	4158.9	8.9274
900	2.70656	3856.3	4397.7	9.4598	1.80417	3856.0	4397.3	9.2725	1.35298	3855.7	4396.9	9.1394
1000	2.93755	4054.8	4642.3	9.6599	1.95824	4054.5	4642.0	9.4726	1.46859	4054.3	4641.7	9.3396
1100	3.16848	4259.6	4893.3	9.8497	2.11226	4259.4	4893.1	9.6624	1.58414	4259.2	4892.9	9.5295
1200	3.39938	4470.5	5150.4	10.0304	2.26624	4470.3	5150.2	9.8431	1.69966	4470.2	5150.0	9.7102
1300	3.63026	4687.1	5413.1	10.2029	2.42019	4686.9	5413.0	10.0157	1.81516	4686.7	5412.8	9.8828
	P = 0.50 MPa (151.83°C)				*P* = 0.60 MPa (158.83°C)				*P* = 0.80 MPa (170.41°C)			
Sat.	0.37483	2560.7	2748.1	6.8207	0.31560	2566.8	2756.2	6.7593	0.24035	2576.0	2768.3	6.6616
200	0.42503	2643.3	2855.8	7.0610	0.35212	2639.4	2850.6	6.9683	0.26088	2631.1	2839.8	6.8177
250	0.47443	2723.8	2961.0	7.2725	0.39390	2721.2	2957.6	7.1833	0.29321	2715.9	2950.4	7.0402
300	0.52261	2803.3	3064.6	7.4614	0.43442	2801.4	3062.0	7.3740	0.32416	2797.5	3056.9	7.2345
350	0.57015	2883.0	3168.1	7.6346	0.47428	2881.6	3166.1	7.5481	0.35442	2878.6	3162.2	7.4107
400	0.61731	2963.7	3272.4	7.7956	0.51374	2962.5	3270.8	7.7097	0.38429	2960.2	3267.7	7.5735
500	0.71095	3129.0	3484.5	8.0893	0.59200	3128.2	3483.4	8.0041	0.44332	3126.6	3481.3	7.8692
600	0.80409	3300.4	3702.5	8.3544	0.66976	3299.8	3701.7	8.2695	0.50186	3298.7	3700.1	8.1354
700	0.89696	3478.6	3927.0	8.5978	0.74725	3478.1	3926.4	8.5132	0.56011	3477.2	3925.3	8.3794
800	0.98966	3663.6	4158.4	8.8240	0.82457	3663.2	4157.9	8.7395	0.61820	3662.5	4157.0	8.6061
900	1.08227	3855.4	4396.6	9.0362	0.90179	3855.1	4396.2	8.9518	0.67619	3854.5	4395.5	8.8185
1000	1.17480	4054.0	4641.4	9.2364	0.97893	4053.8	4641.1	9.1521	0.73411	4053.3	4640.5	9.0189
1100	1.26728	4259.0	4892.6	9.4263	1.05603	4258.8	4892.4	9.3420	0.79197	4258.3	4891.9	9.2090
1200	1.35972	4470.0	5149.8	9.6071	1.13309	4469.8	5149.6	9.5229	0.84980	4469.4	5149.3	9.3898
1300	1.45214	4686.6	5412.6	9.7797	1.21012	4686.4	5412.5	9.6955	0.90761	4686.1	5412.2	9.5625

*The temperature in parentheses is the saturation temperature at the specified pressure.

† Properties of saturated vapor at the specified pressure.

TABLE A–6

Superheated water (*Continued*)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 4.0 MPa (250.35°C)				*P* = 4.5 MPa (257.44°C)				*P* = 5.0 MPa (263.94°C)			
Sat.	0.04978	2601.7	2800.8	6.0696	0.04406	2599.7	2798.0	6.0198	0.03945	2597.0	2794.2	5.9737
275	0.05461	2668.9	2887.3	6.2312	0.04733	2651.4	2864.4	6.1429	0.04144	2632.3	2839.5	6.0571
300	0.05887	2726.2	2961.7	6.3639	0.05138	2713.0	2944.2	6.2854	0.04535	2699.0	2925.7	6.2111
350	0.06647	2827.4	3093.3	6.5843	0.05842	2818.6	3081.5	6.5153	0.05197	2809.5	3069.3	6.4516
400	0.07343	2920.8	3214.5	6.7714	0.06477	2914.2	3205.7	6.7071	0.05784	2907.5	3196.7	6.6483
450	0.08004	3011.0	3331.2	6.9386	0.07076	3005.8	3324.2	6.8770	0.06332	3000.6	3317.2	6.8210
500	0.08644	3100.3	3446.0	7.0922	0.07652	3096.0	3440.4	7.0323	0.06858	3091.8	3434.7	6.9781
600	0.09886	3279.4	3674.9	7.3706	0.08766	3276.4	3670.9	7.3127	0.07870	3273.3	3666.9	7.2605
700	0.11098	3462.4	3906.3	7.6214	0.09850	3460.0	3903.3	7.5647	0.08852	3457.7	3900.3	7.5136
800	0.12292	3650.6	4142.3	7.8523	0.10916	3648.8	4140.0	7.7962	0.09816	3646.9	4137.7	7.7458
900	0.13476	3844.8	4383.9	8.0675	0.11972	3843.3	4382.1	8.0118	0.10769	3841.8	4380.2	7.9619
1000	0.14653	4045.1	4631.2	8.2698	0.13020	4043.9	4629.8	8.2144	0.11715	4042.6	4628.3	8.1648
1100	0.15824	4251.4	4884.4	8.4612	0.14064	4250.4	4883.2	8.4060	0.12655	4249.3	4882.1	8.3566
1200	0.16992	4463.5	5143.2	8.6430	0.15103	4462.6	5142.2	8.5880	0.13592	4461.6	5141.3	8.5388
1300	0.18157	4680.9	5407.2	8.8164	0.16140	4680.1	5406.5	8.7616	0.14527	4679.3	5405.7	8.7124
	P = 6.0 MPa (275.59°C)				*P* = 7.0 MPa (285.83°C)				*P* = 8.0 MPa (295.01°C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266
550	0.06102	3175.2	3541.3	7.0308	0.051966	3167.9	3531.6	6.9507	0.045172	3160.5	3521.8	6.8800
600	0.06527	3267.2	3658.8	7.1693	0.055665	3261.0	3650.6	7.0910	0.048463	3254.7	3642.4	7.0221
700	0.07355	3453.0	3894.3	7.4247	0.062850	3448.3	3888.3	7.3487	0.054829	3443.6	3882.2	7.2822
800	0.08165	3643.2	4133.1	7.6582	0.069856	3639.5	4128.5	7.5836	0.061011	3635.7	4123.8	7.5185
900	0.08964	3838.8	4376.6	7.8751	0.076750	3835.7	4373.0	7.8014	0.067082	3832.7	4369.3	7.7372
1000	0.09756	4040.1	4625.4	8.0786	0.083571	4037.5	4622.5	8.0055	0.073079	4035.0	4619.6	7.9419
1100	0.10543	4247.1	4879.7	8.2709	0.090341	4245.0	4877.4	8.1982	0.079025	4242.8	4875.0	8.1350
1200	0.11326	4459.8	5139.4	8.4534	0.097075	4457.9	5137.4	8.3810	0.084934	4456.1	5135.5	8.3181
1300	0.12107	4677.7	5404.1	8.6273	0.103781	4676.1	5402.6	8.5551	0.090817	4674.5	5401.0	8.4925
	P = 9.0 MPa (303.35°C)				*P* = 10.0 MPa (311.00°C)				*P* = 12.5 MPa (327.81°C)			
Sat.	0.020489	2558.5	2742.9	5.6791	0.018028	2545.2	2725.5	5.6159	0.013496	2505.6	2674.3	5.4638
325	0.023284	2647.6	2857.1	5.8738	0.019877	2611.6	2810.3	5.7596				
350	0.025816	2725.0	2957.3	6.0380	0.022440	2699.6	2924.0	5.9460	0.016138	2624.9	2826.6	5.7130
400	0.029960	2849.2	3118.8	6.2876	0.026436	2833.1	3097.5	6.2141	0.020030	2789.6	3040.0	6.0433
450	0.033524	2956.3	3258.0	6.4872	0.029782	2944.5	3242.4	6.4219	0.023019	2913.7	3201.5	6.2749
500	0.036793	3056.3	3387.4	6.6603	0.032811	3047.0	3375.1	6.5995	0.025630	3023.2	3343.6	6.4651
550	0.039885	3153.0	3512.0	6.8164	0.035655	3145.4	3502.0	6.7585	0.028033	3126.1	3476.5	6.6317
600	0.042861	3248.4	3634.1	6.9605	0.038378	3242.0	3625.8	6.9045	0.030306	3225.8	3604.6	6.7828
650	0.045755	3343.4	3755.2	7.0954	0.041018	3338.0	3748.1	7.0408	0.032491	3324.1	3730.2	6.9227
700	0.048589	3438.8	3876.1	7.2229	0.043597	3434.0	3870.0	7.1693	0.034612	3422.0	3854.6	7.0540
800	0.054132	3632.0	4119.2	7.4606	0.048629	3628.2	4114.5	7.4085	0.038724	3618.8	4102.8	7.2967
900	0.059562	3829.6	4365.7	7.6802	0.053547	3826.5	4362.0	7.6290	0.042720	3818.9	4352.9	7.5195
1000	0.064919	4032.4	4616.7	7.8855	0.058391	4029.9	4613.8	7.8349	0.046641	4023.5	4606.5	7.7269
1100	0.070224	4240.7	4872.7	8.0791	0.063183	4238.5	4870.3	8.0289	0.050510	4233.1	4864.5	7.9220
1200	0.075492	4454.2	5133.6	8.2625	0.067938	4452.4	5131.7	8.2126	0.054342	4447.7	5127.0	8.1065
1300	0.080733	4672.9	5399.5	8.4371	0.072667	4671.3	5398.0	8.3874	0.058147	4667.3	5394.1	8.2819