CAE 208 / MMAE 320: Thermodynamics
Fall 2023

September 26, 2023
Properties of Pure Substances (3)

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Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
muh182@iit.edu

ANNOUNCEMENTS

Announcements

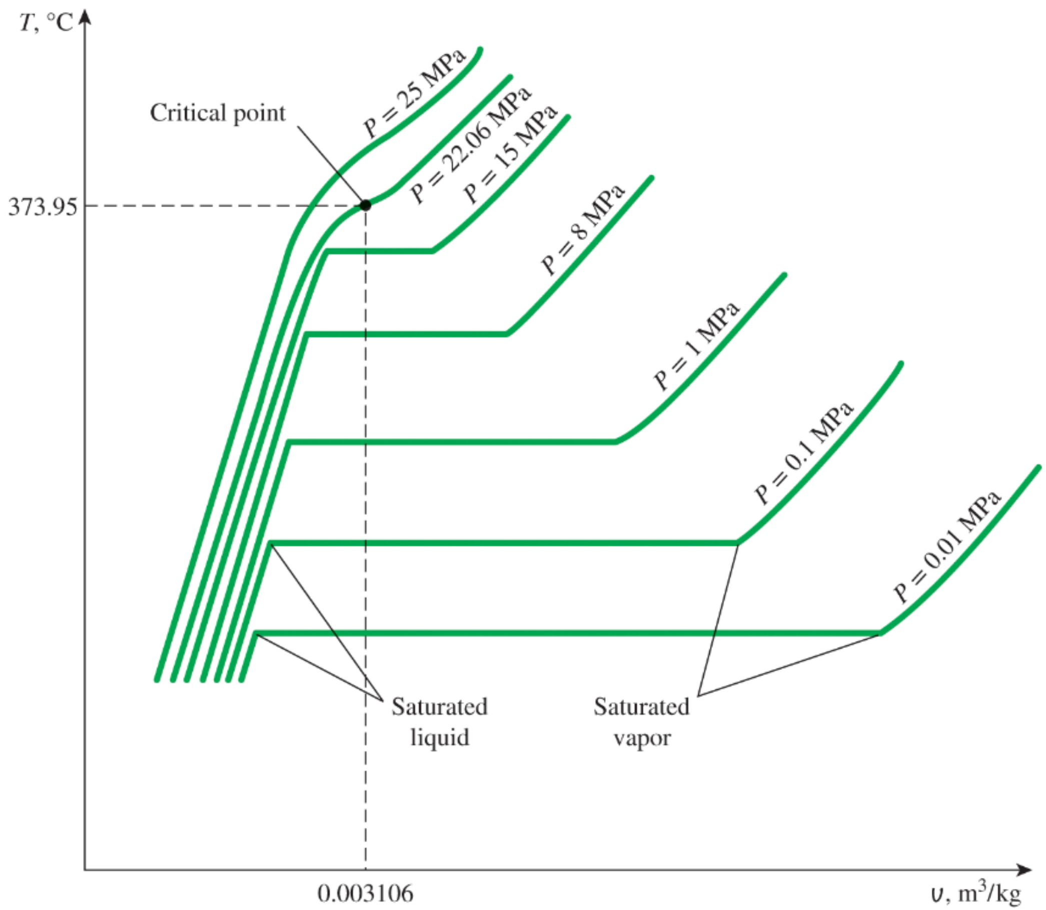
- Assignment 4 is due this coming Thursday

- Midterm is currently scheduled for October 10:
  - Should we change the date?
  - How should you get ready for the exam?

RECAP

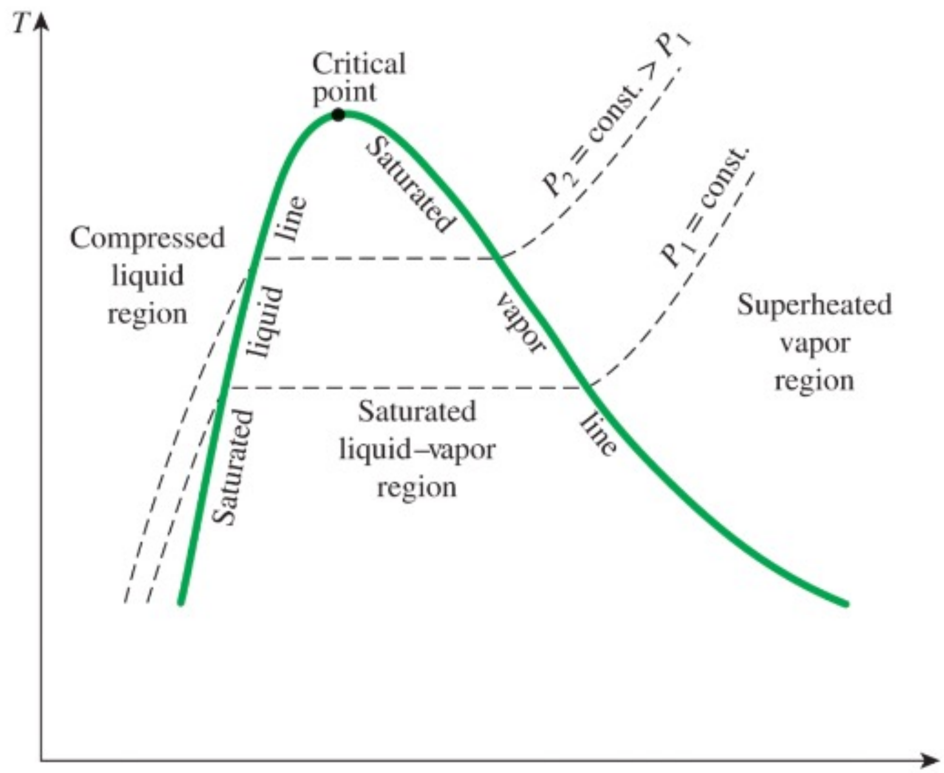
Recap

- We always look at the property diagrams in this course



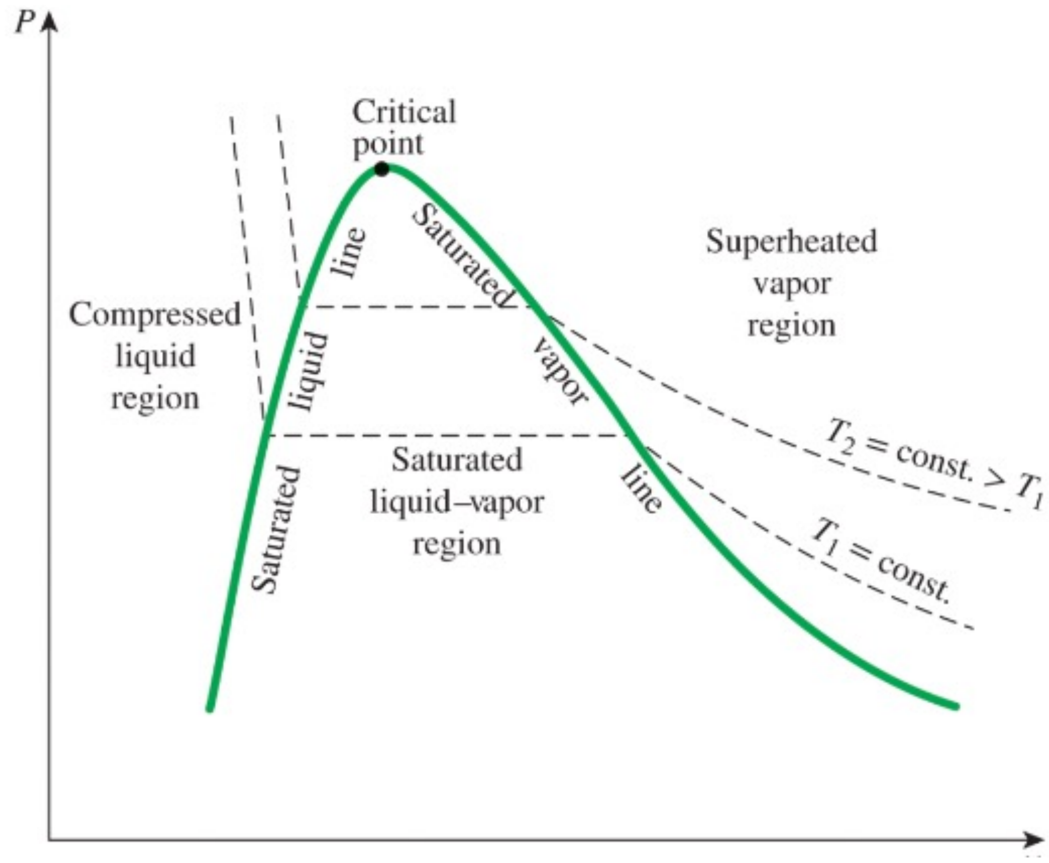
Recap

- The saturated liquid states can be connected by a line called saturated liquid line and similarly the saturated vapor line



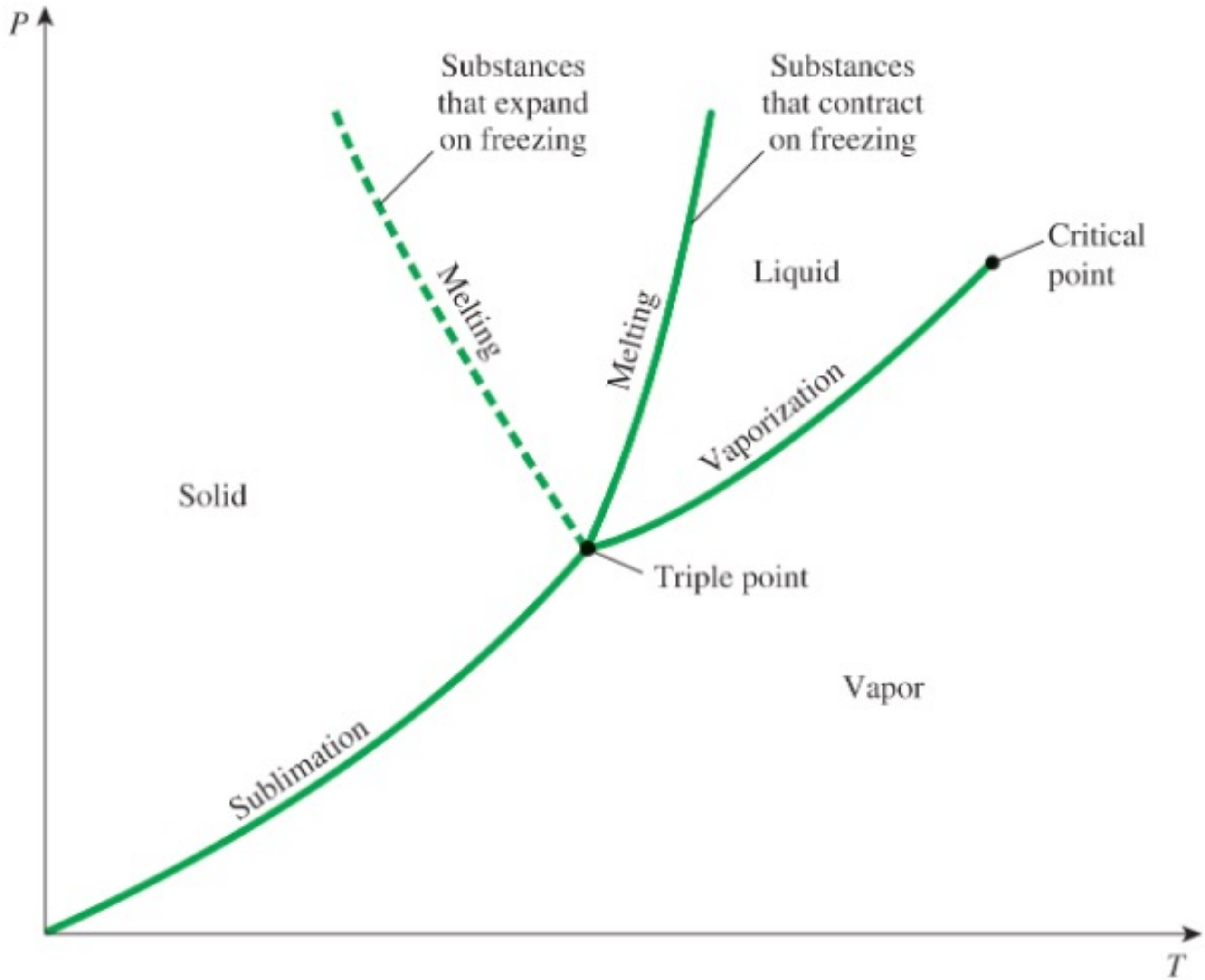
Recap

- The P-v diagram of a pure substance is very much like the T-v diagram but T = constant lines on this diagram have a downward trend



Recap

- P-T diagram is known as the phase diagram



Recap

APPENDIX 1

PROPERTY TABLES AND CHARTS (SI UNITS)

See the references folder on Blackboard

Recap

APPENDIX 2

PROPERTY TABLES AND CHARTS (ENGLISH UNITS)

See the references folder on Blackboard

Recap

- Table A-4 and Table A-5

TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	*Specific volume,* m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
		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
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3

Recap

- Table A-4 and Table A-5

TABLE A–5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	*Specific volume,* m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
		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
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7

Recap

- Table A-6 for superheated

TABLE A–6

Superheated water

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
	$P = 0.01$ MPa (45.81°C)*				$P = 0.05$ MPa (81.32°C)				
Sat.†	14.670	2437.2	2583.9	8.1488	3.2403	2483.2	2645.2	7.5931	1.6941
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
150	19.513	2587.9	2783.0	8.6893	3.8897	2585.7	2780.2	7.9413	1.9367
200	21.826	2661.4	2879.6	8.9049	4.3562	2660.0	2877.8	8.1592	2.1724
250	24.136	2736.1	2977.5	9.1015	4.8206	2735.1	2976.2	8.3568	2.4062
300	26.446	2812.3	3076.7	9.2827	5.2841	2811.6	3075.8	8.5387	2.6389
400	31.063	2969.3	3280.0	9.6094	6.2094	2968.9	3279.3	8.8659	3.1027

Recap

- Table A-7 for compressed liquid

TABLE A–7

Compressed liquid 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
	P = 5 MPa (263.94°C)				P = 10 MPa (311.00°C)				
Sat.	0.0012862	1148.1	1154.5	2.9207	0.0014522	1393.3	1407.9	3.3603	0.0016572
0	0.0009977	0.04	5.03	0.0001	0.0009952	0.12	10.07	0.0003	0.0009928
20	0.0009996	83.61	88.61	0.2954	0.0009973	83.31	93.28	0.2943	0.0009951
40	0.0010057	166.92	171.95	0.5705	0.0010035	166.33	176.37	0.5685	0.0010013
60	0.0010149	250.29	255.36	0.8287	0.0010127	249.43	259.55	0.8260	0.0010105
80	0.0010267	333.82	338.96	1.0723	0.0010244	332.69	342.94	1.0691	0.0010221
100	0.0010410	417.65	422.85	1.3034	0.0010385	416.23	426.62	1.2996	0.0010361
120	0.0010576	501.91	507.19	1.5236	0.0010549	500.18	510.73	1.5191	0.0010522
140	0.0010769	586.80	592.18	1.7344	0.0010738	584.72	595.45	1.7293	0.0010708
160	0.0010988	672.55	678.04	1.9374	0.0010954	670.06	681.01	1.9316	0.0010920

CLASS ACTIVITY

Class Activity

- A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.

Class Activity

- Solution:

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg		
		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
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0

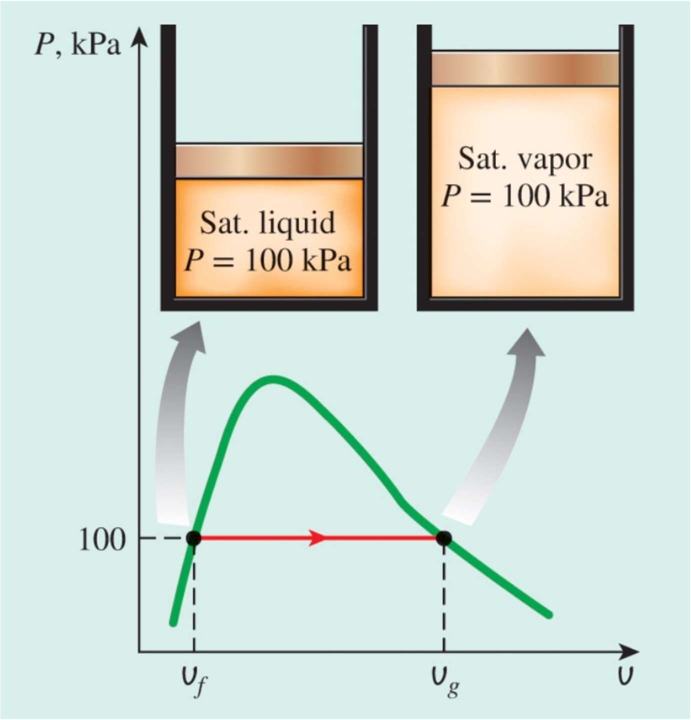
Class Activity

- Solution:

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931\, m^3/kg$$

$$\Delta V = mv_{fg} = (0.2\, kg)\left(1.6931 \frac{m^3}{kg}\right) = 0.3386\, m^3$$

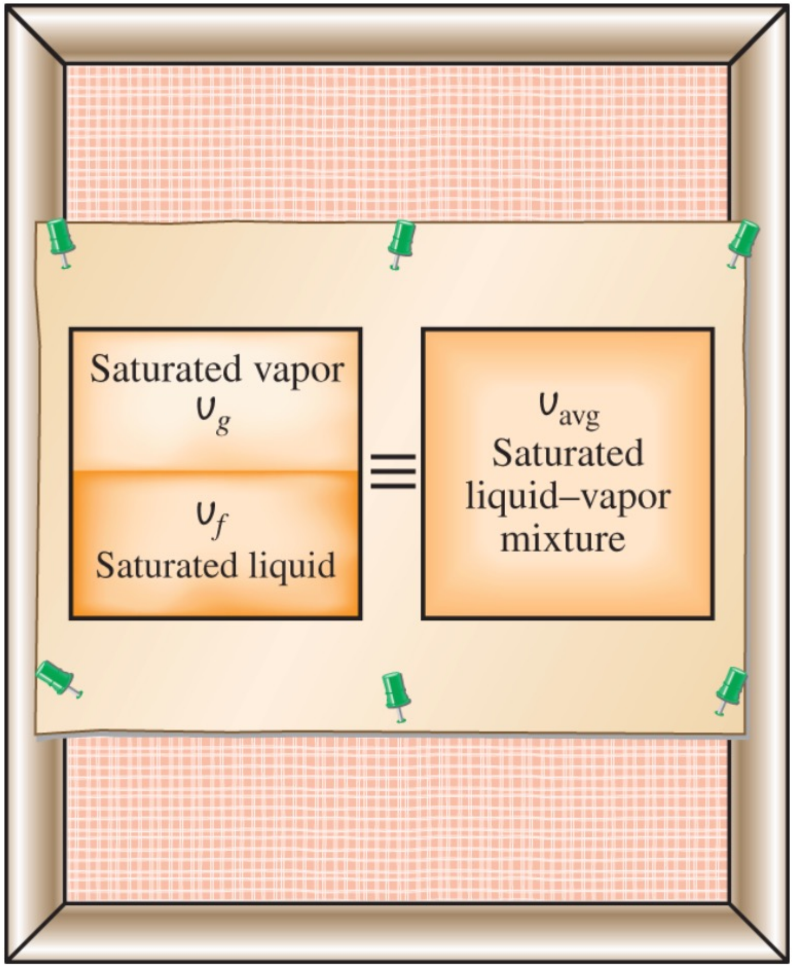
$$mh_{fg} = (0.2\, kg)\left(22575.5 \frac{kJ}{kg}\right) = 451.5\, kJ$$



SATURATED LIQUID-VAPOR MIXTURE

Saturated Liquid-Vapor Mixture

- During a vaporization process, a substance exists as part liquid and part vapor

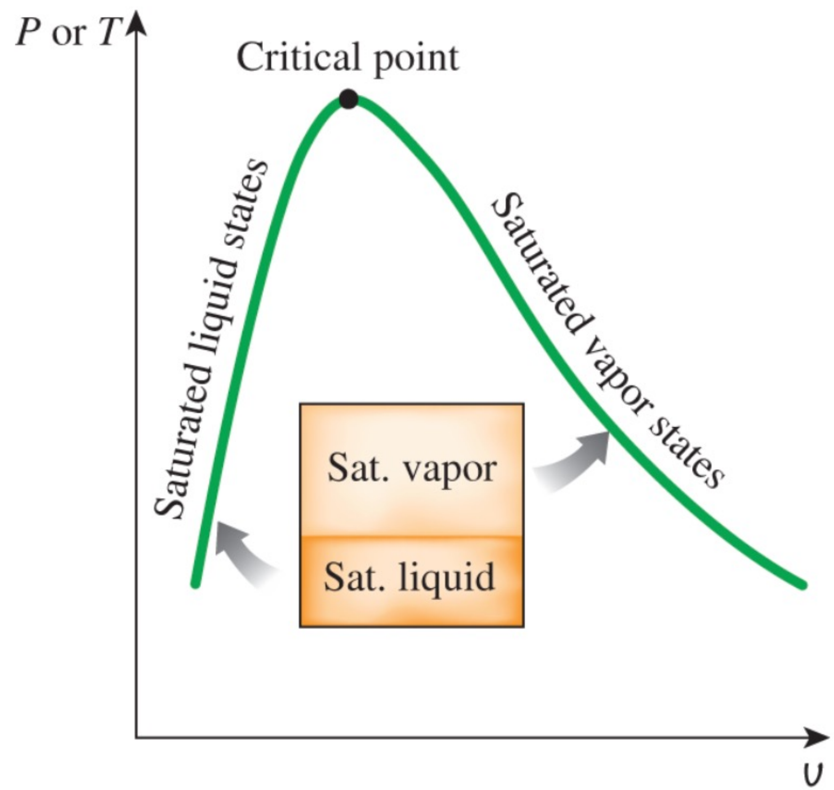


Saturated Liquid-Vapor Mixture

- For the saturated liquid-vapor mixture, we need to define a new property named "quality"

$$x = \frac{m_{vapor}}{m_{total}}$$

$$m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$$



Saturated Liquid-Vapor Mixture

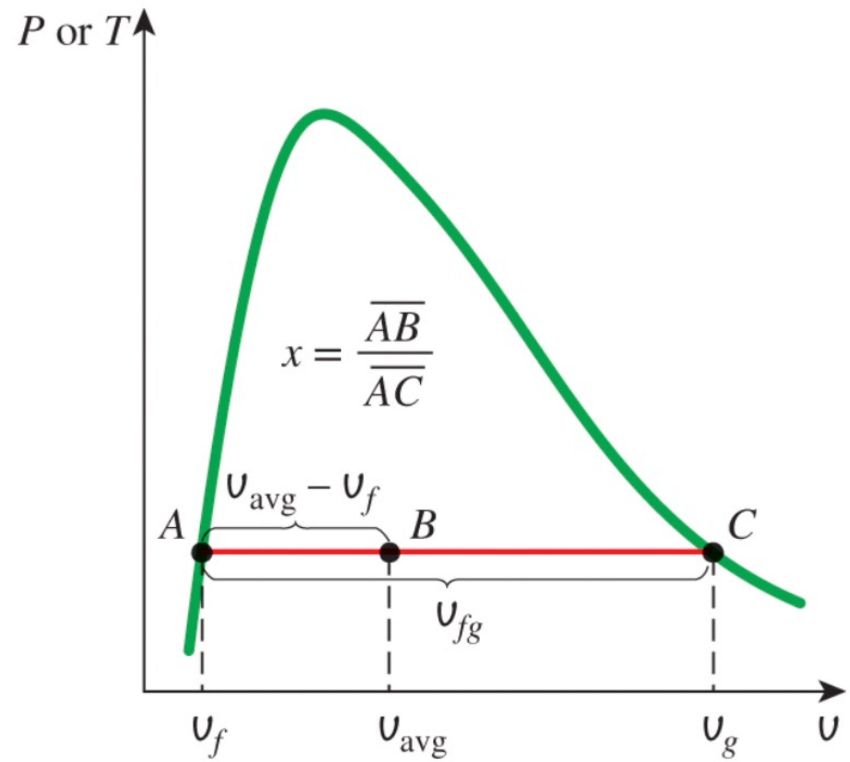
- We can write:

$$V = V_f + V_g$$

$$m_t = m_f + m_g$$

$$v_{avg} = v_f + x v_{fg}$$

$$x = \frac{v_{avg} - v_f}{v_{fg}}$$



Saturated Liquid-Vapor Mixture

- How can we derive this equation for v_{avg}?

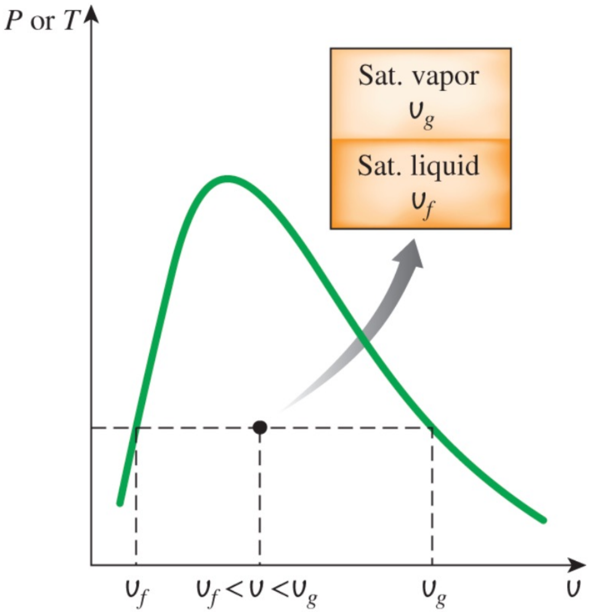
Saturated Liquid-Vapor Mixture

- We can write:

$$v_{avg} = v_f + xv_{fg}$$

$$u_{avg} = u_f + uv_{fg}$$

$$h_{avg} = h_f + hv_{fg}$$



CLASS ACTIVITY

Class Activity

- A rigid tank contains 10 kg of water at 90 °C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (a) the pressure in the tank and (b) the volume of the tank.

Class Activity

- Solution:

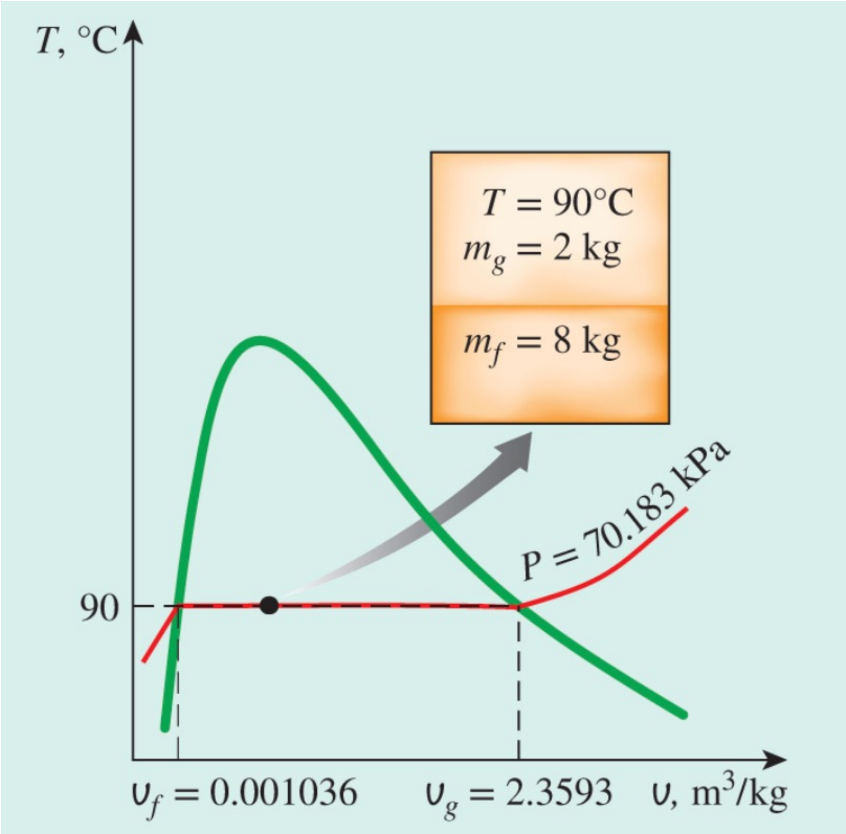
TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg		
		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
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6

Class Activity

- Solution:



Class Activity

- Part (b) – Solution 1

$$V = V_f + V_g = m_f v_f + m_g v_g$$

$$V = (8\ kg)\left(0.001036\,\frac{m^3}{kg}\right) + (2\ kg)\left(2.3593\,\frac{m^3}{kg}\right) = 4.73\ m^3$$

$$V = 4.73\ m^3$$

Class Activity

- Part (b) – Solution 2:

$$x = \frac{m_g}{m_t} = \frac{2}{2+8} = 0.2$$

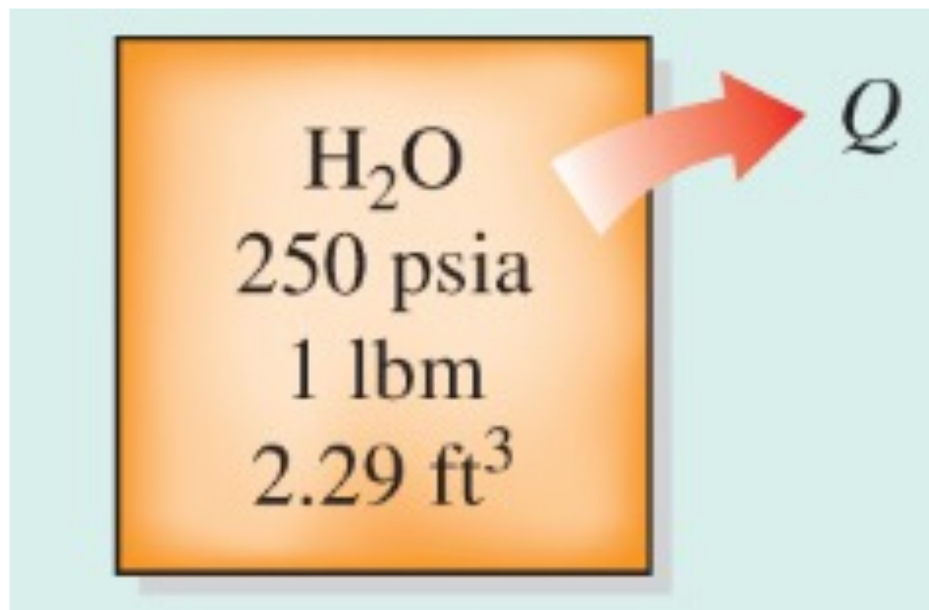
$$v = v_f + xv_{fg} = \left(0.001036\,\frac{m^3}{kg}\right) + (0.2)\left(2.3593 - 0.001036\,\frac{m^3}{kg}\right) = 0.473\,\frac{m^3}{kg}$$

$$V = mv = (10\ kg)\left(0.473\,\frac{m^3}{kg}\right) = 4.73\ m^3$$

CLASS ACTIVITY

Class Activity

- One pound-mass of water fills a 2.29 ft^3 rigid container at an initial pressure of 250 psia. The container is then cooled to 100 °F. Determine the initial temperature and final pressure of the water.



Class Activity

- Solution:

$$v_i = \frac{V}{m} = \frac{2.29\ ft^3}{1\ lbm} = 2.29\,\frac{ft^3}{lbm}$$

TABLE A–5E

Saturated water—Pressure table

Press., P psia	Sat. temp., T_{sat} °F	*Specific volume,* ft^3/lbm Sat. liquid, v_f	Sat. vapor, v_g	*Internal energy,* Bt Sat. liquid, u_f	Evap., u_{fg}
1	101.69	0.01614	333.49	69.72	973.99
2	126.02	0.01623	173.71	94.02	957.45
3	141.41	0.01630	118.70	109.39	946.90
4	152.91	0.01636	90.629	120.89	938.97
5	162.18	0.01641	73.525	130.17	932.53
190	377.52	0.01833	2.4040	350.24	763.31
200	381.80	0.01839	2.2882	354.78	759.32
250	400.97	0.01865	1.8440	375.23	741.02
300	417.35	0.01890	1.5435	392.89	724.77
350	431.74	0.01912	1.3263	408.55	709.98

$$v_i > v_g$$

Class Activity

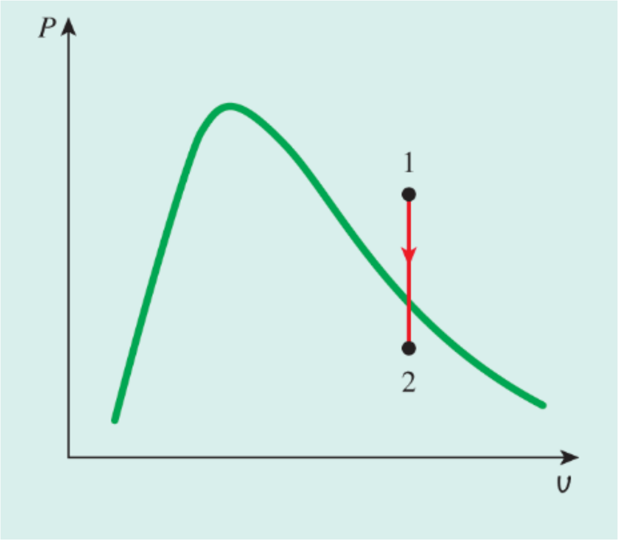
- Solution:

TABLE A–6E				
Superheated water				
T °F	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R
	P = 250 psia (400.97°F)			
Sat.	1.8440	1116.3	1201.6	1.5270
450	2.0027	1141.3	1234.0	1.5636
500	2.1506	1164.1	1263.6	1.5953
550	2.2910	1185.6	1291.5	1.6237
600	2.4264	1206.3	1318.6	1.6499
650	2.5586	1226.8	1345.1	1.6743

$$\begin{cases} P_1 = 250\ psia \\ v_1 = 2.29\ ft^3/lbm \end{cases}$$

Class Activity

- Solution:



$$T_2 = 100\ °F$$

$$v_2 = v_1 = 2.29\ ft^3/lbm$$

$$P_2 = P_{sat\ @\ 100\ F} = 20.9505\ psia$$

CLASS ACTIVITY

Class Activity

- Determine temperature of water at a state of P = 0.5 MPa and h = 2,890 kJ/kg.

Class Activity

- Solution:

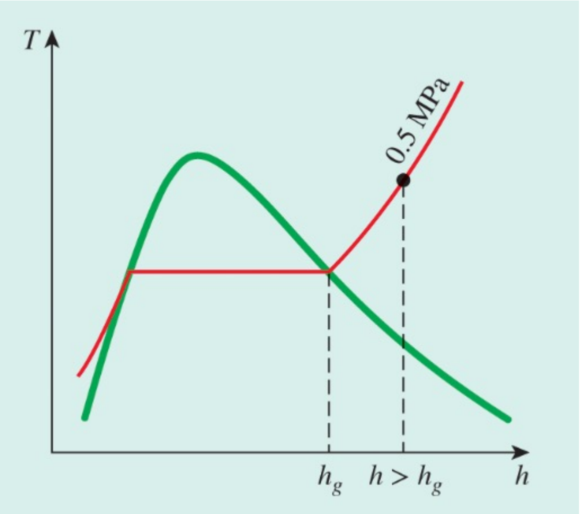


TABLE A–5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1

Class Activity

- Solution:

TABLE A–6

Superheated water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$P = 0.50$ MPa (151.83°C)			
Sat.	0.37483	2560.7	2748.1	6.8207
200	0.42503	2643.3	2855.8	7.0610
250	0.47443	2723.8	2961.0	7.2725
300	0.52261	2803.3	3064.6	7.4614
350	0.57015	2883.0	3168.1	7.6346
400	0.61731	2963.7	3272.4	7.7956
500	0.71095	3129.0	3484.5	8.0893
600	0.80409	3300.4	3702.5	8.3544

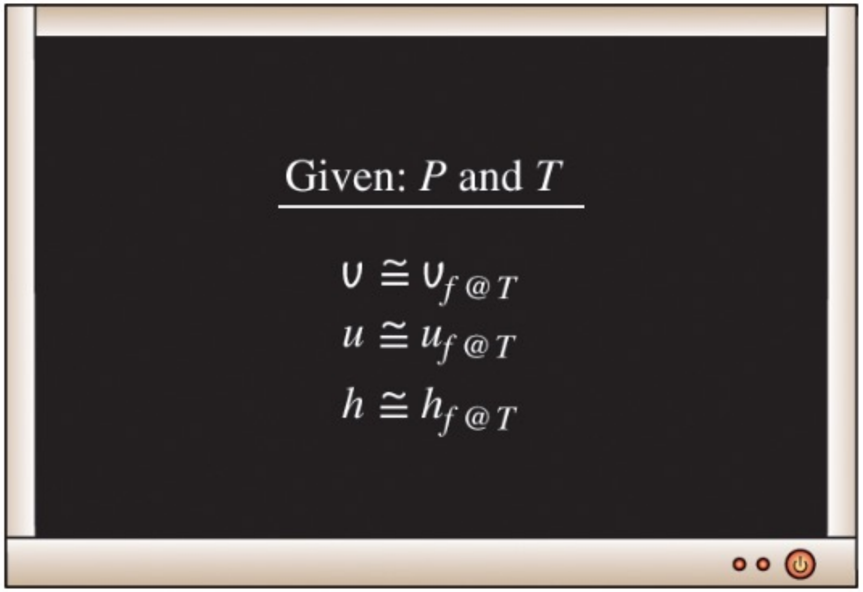
$$T = 216.3\,°C$$

COMPRESSED LIQUID

Compressed Liquid

- Compressed liquid tables are not as commonly available (Table A-7)

- In the absence of compressed liquid data, a general approximation is to treat compressed liquid as saturated liquid at the given temperature



Compressed Liquid

- At low to moderate pressures and temperatures, we can say:

$$h \sim h_{f\ @\ T} + v_{f\ @\ T}(P - P_{sat\ @\ T})$$

Compressed Liquid

- In general, a compressed liquid is characterized by:

Higher pressures ($P > P_{sat}$ at a given T)

Lower temperatures ($T < T_{sat}$ at a given P)

Lower specific volumes ($v < v_f$ at a given P or T)

Lower internal energies ($u < u_f$ at a given P or T)

Lower enthalpies ($h < h_f$ at a given P or T)

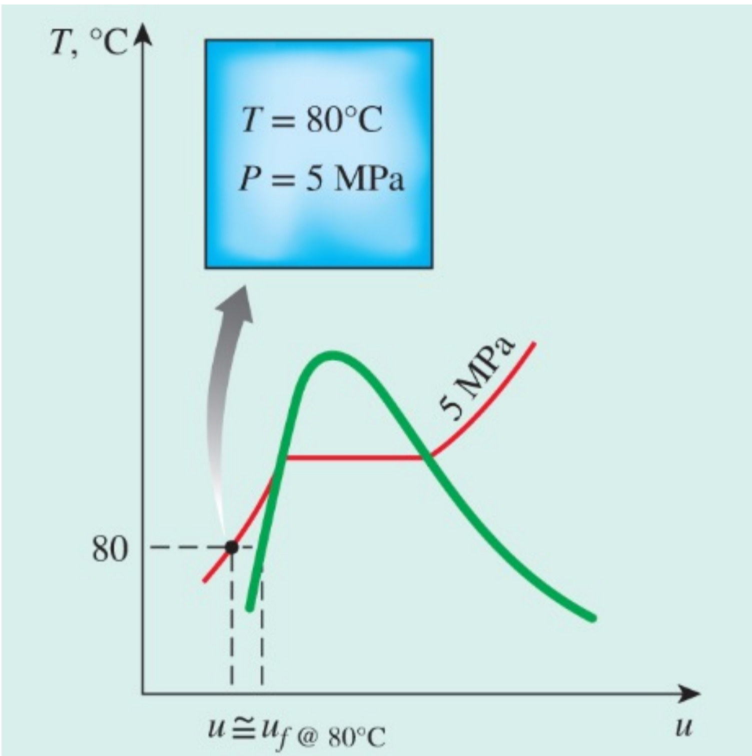
CLASS ACTIVITY

Class Activity

- Determine the internal energy of compressed liquid water at 80 °C and 5 MPa, using (a) data from compressed liquid table and (b) saturated liquid data. What is the error involved in the second case.

Class Activity

- Solution:



Class Activity

- Solution:

TABLE A–7

Compressed liquid water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$P = 5$ MPa (263.94°C)			
Sat.	0.0012862	1148.1	1154.5	2.9207
0	0.0009977	0.04	5.03	0.0001
20	0.0009996	83.61	88.61	0.2954
40	0.0010057	166.92	171.95	0.5705
60	0.0010149	250.29	255.36	0.8287
80	0.0010267	333.82	338.96	1.0723
100	0.0010410	417.65	422.85	1.3034

Class Activity

- Solution:

TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	*Specific volume,* m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
		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
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0

Class Activity

- Solution:

$$Error = \frac{334.94 - 333.82}{333.82} \times 100 = 0.34\ \%$$

THE IDEAL-GAS EQUATION OF STATE

The Ideal-Gas Equation of State

- Property tables provide very accurate information about the properties, but they are
  - ❑ Bulky
  - ❑ Vulnerable to typographical errors

- It would be nice to have a simple relationship

The Ideal-Gas Equation of State

- Any equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state (there simple and complex ones)

- We used vapor and gas often interchangeably in the first three chapters

The Ideal-Gas Equation of State

- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state

$$P = R\left(\frac{T}{v}\right)$$

$$Pv = RT$$

Ideal—gas equation of state

The Ideal-Gas Equation of State

- We can define gas constant for each gas:

$$R = \frac{R_u}{M} \qquad \left(\frac{kJ}{kg.K} \; or \; \frac{kPa.m^3}{kg.K}\right)$$

R_u is the universal gas constant

$$R_u = \begin{cases} 8.31447 \text{ kJ/kmol} \cdot \text{K} \\ 8.31447 \text{ kPa} \cdot \text{m}^3\text{/kmol} \cdot \text{K} \\ 0.0831447 \text{ bar} \cdot \text{m}^3\text{/kmol} \cdot \text{K} \\ 1.98588 \text{ Btu/lbmol} \cdot \text{R} \\ 10.7316 \text{ psia} \cdot \text{ft}^3\text{/lbmol} \cdot \text{R} \\ 1545.37 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R} \end{cases}$$

The Ideal-Gas Equation of State

- Examples of gas constant for a few known gases:

Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

The Ideal-Gas Equation of State

- M is the molar mass
  - ❑ The mass of one mole of a substance in grams or the mas of kmol in kilograms
  - ❑ Or, the mass of 1 lbmol in lbm

(e.g., for Nitrogen we have N = 28 kg/kmol = 28 lbm/lbmol)

The Ideal-Gas Equation of State

- Several variations of the ideal-gas equation of state

$$N = \frac{m}{M}$$

TABLE A–1

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, *M* kg/kmol	Gas constant, *R* kJ/kg · K*	*Critical-p*	
				Temperature, K	Pressur
Air	–	28.97	0.2870	132.5	3.
Ammonia	NH_3	17.03	0.4882	405.5	11.
Argon	Ar	39.948	0.2081	151	4.
Benzene	C_6H_6	78.115	0.1064	562	4.
Bromine	Br_2	159.808	0.0520	584	10.
n-Butane	C_4H_{10}	58.124	0.1430	425.2	3.
Carbon dioxide	CO_2	44.01	0.1889	304.2	7.
Carbon monoxide	CO	28.011	0.2968	133	3.
Carbon tetrachloride	CCl_4	153.82	0.05405	556.4	4.
Chlorine	Cl_2	70.906	0.1173	417	7.
Chloroform	$CHCl_3$	119.38	0.06964	536.6	5.
Dichlorodifluoromethane (R-12)	CCl_2F_2	120.91	0.06876	384.7	4.

The Ideal-Gas Equation of State

- Several variations of the ideal-gas equation of state

$$v = \frac{V}{m}$$

$$P\left(\frac{V}{m}\right) = RT \rightarrow PV = mRT$$

The Ideal-Gas Equation of State

- Several variations of the ideal-gas equation of state

$$N = \frac{m}{M}$$

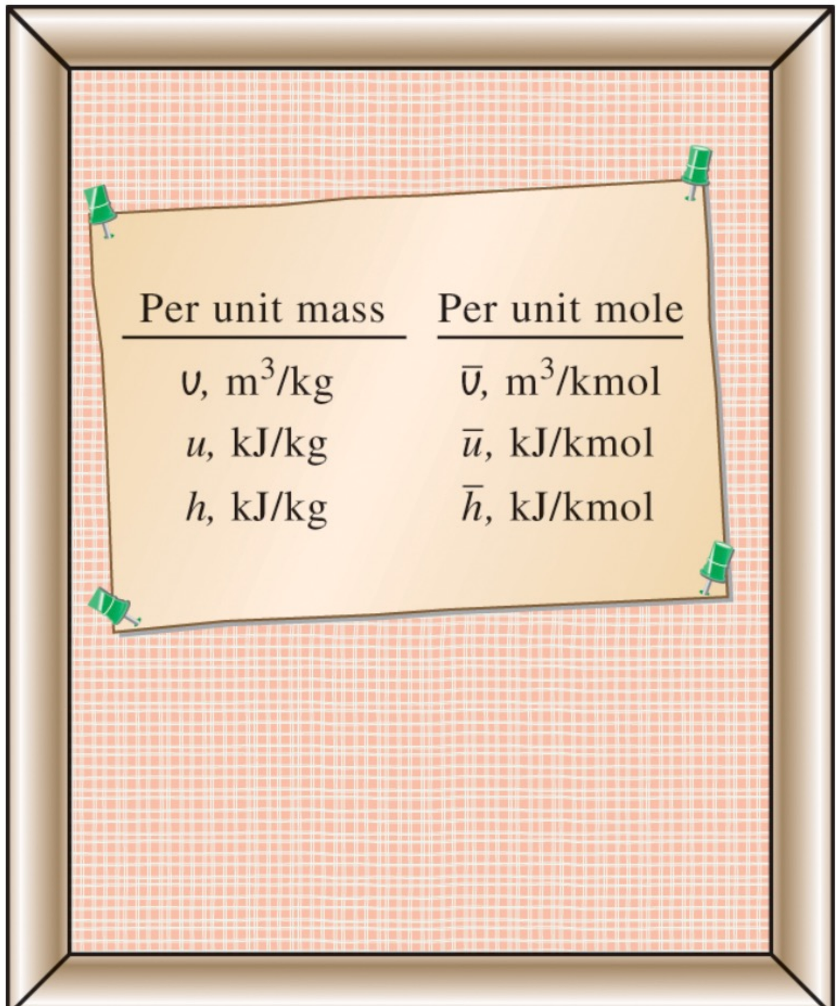
$$PV = (NM)RT$$

$$PV = NR_uT$$

$$P\left(\frac{V}{N}\right) = R_uT \quad \rightarrow P\bar{V} = R_uT$$

The Ideal-Gas Equation of State

- Properties per unit mole are:



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The Ideal-Gas Equation of State

- By writing the equation twice for a fixed mass and simplifying we can write:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

CLASS ACTIVITY

Class Activity

- The gage pressure of an automobile tire is measure to be 210 kPa before a trip and 220 kPa after the trip at a location where the atmospheric pressure is 95 kPa. Assuming the volume of the tire remains constant and the air temperature before the trip is 25 °C, determine air temperature after the trip.

Class Activity

- Solution:

$$P_1 = P_{gage,1} + P_{atm} = 210 + 95 = 305\ kPa$$

$$P_2 = P_{gage,2} + P_{atm} = 220 + 95 = 315\ kPa$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{315\ kPa}{305\ kPa}(25 + 273.15\ K) = 307.8\ K = 34.8\ °C$$

Is Water an Ideal Gas?

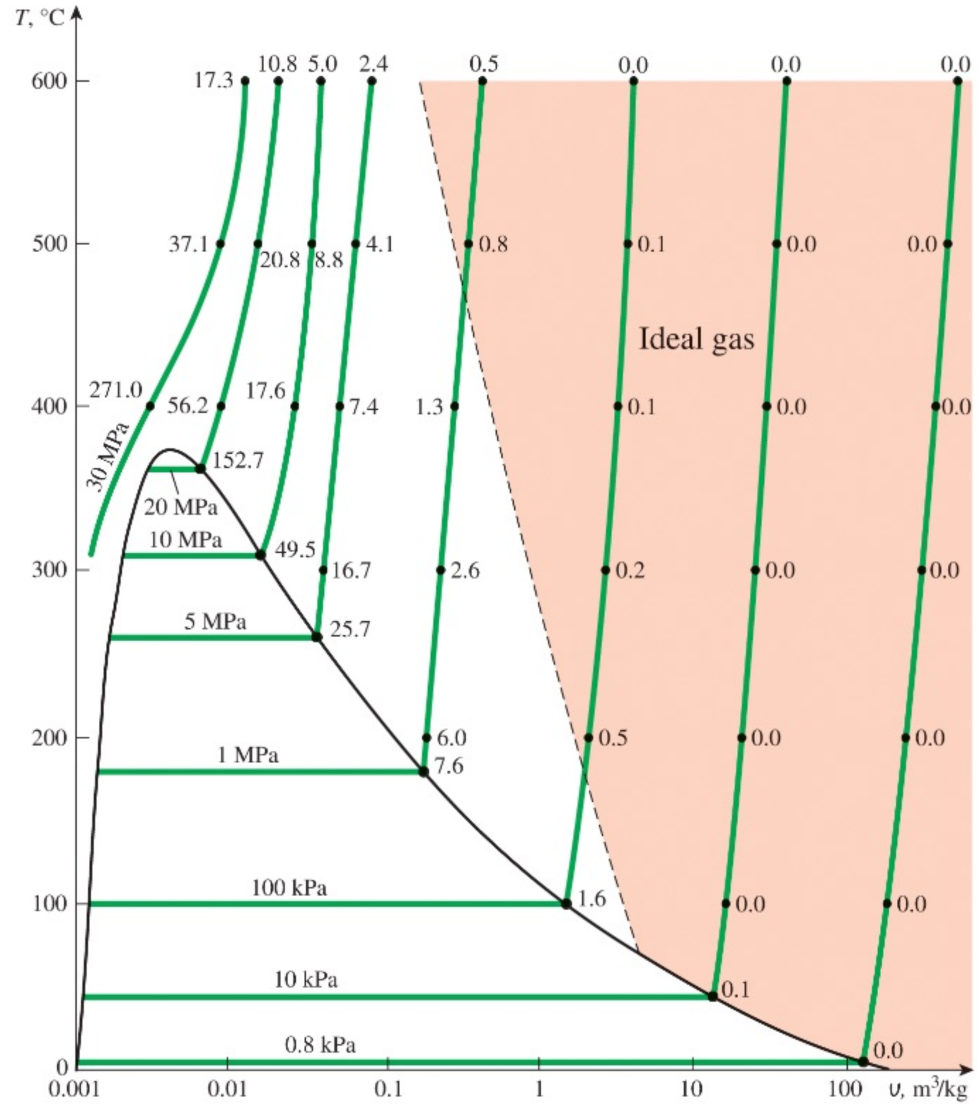


FIGURE 4–46

Percentage of error $([|\upsilon_{table} - \upsilon_{ideal}| / \upsilon_{table}] \times 100)$ involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with les percent error.

COMPRESSIBILITY FACTOR – A MEASURE OF OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility Factor

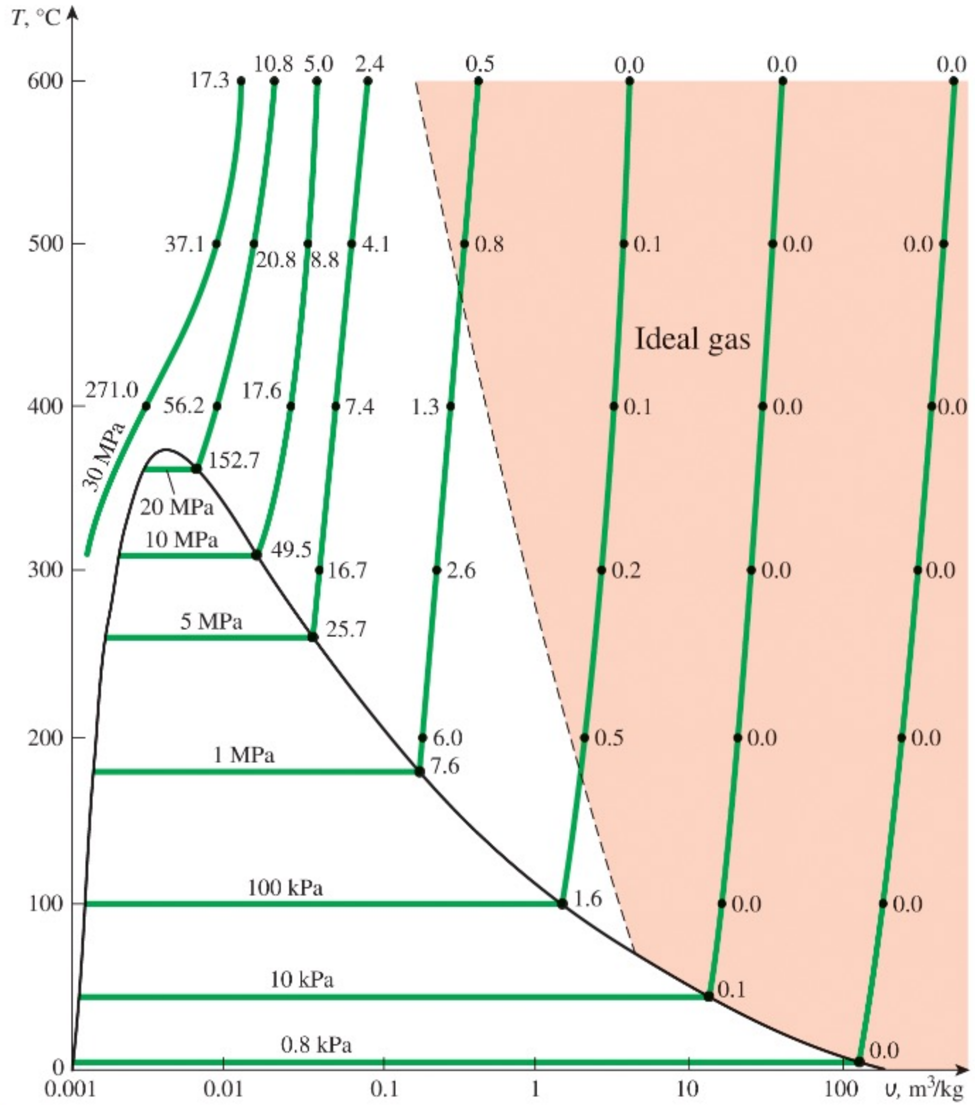


FIGURE 4–46
Percentage of error ($[|\upsilon_{table} - \upsilon_{ideal}| / \upsilon_{table}] \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with les percent error.

Compressibility Factor

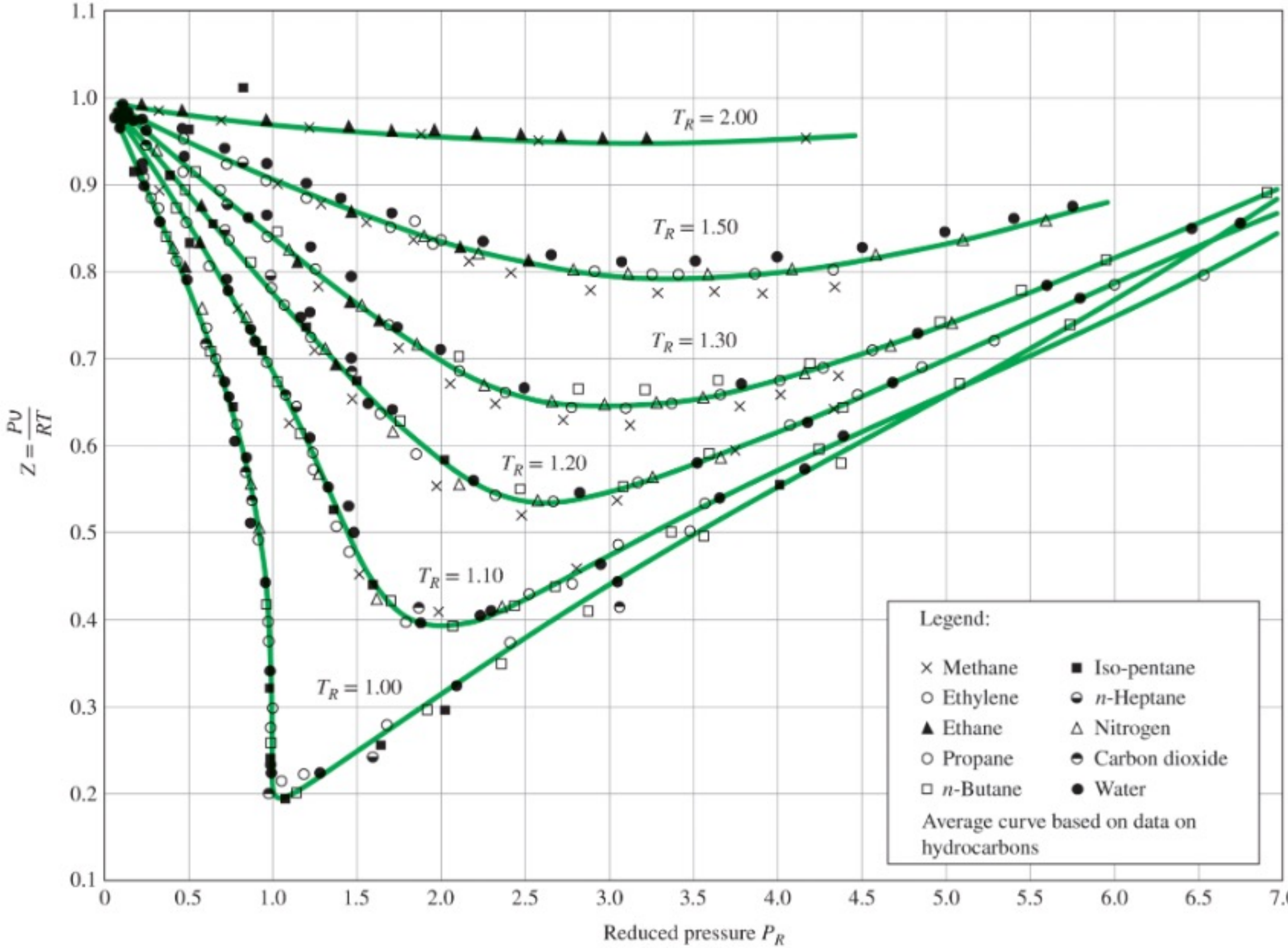
- Z factor for all gases is approximately the same at the same reduced temperature and pressure due to the principle of corresponding states

$$P_R = \frac{P}{P_{cr}}$$

$$T_R = \frac{T}{T_{Cr}}$$

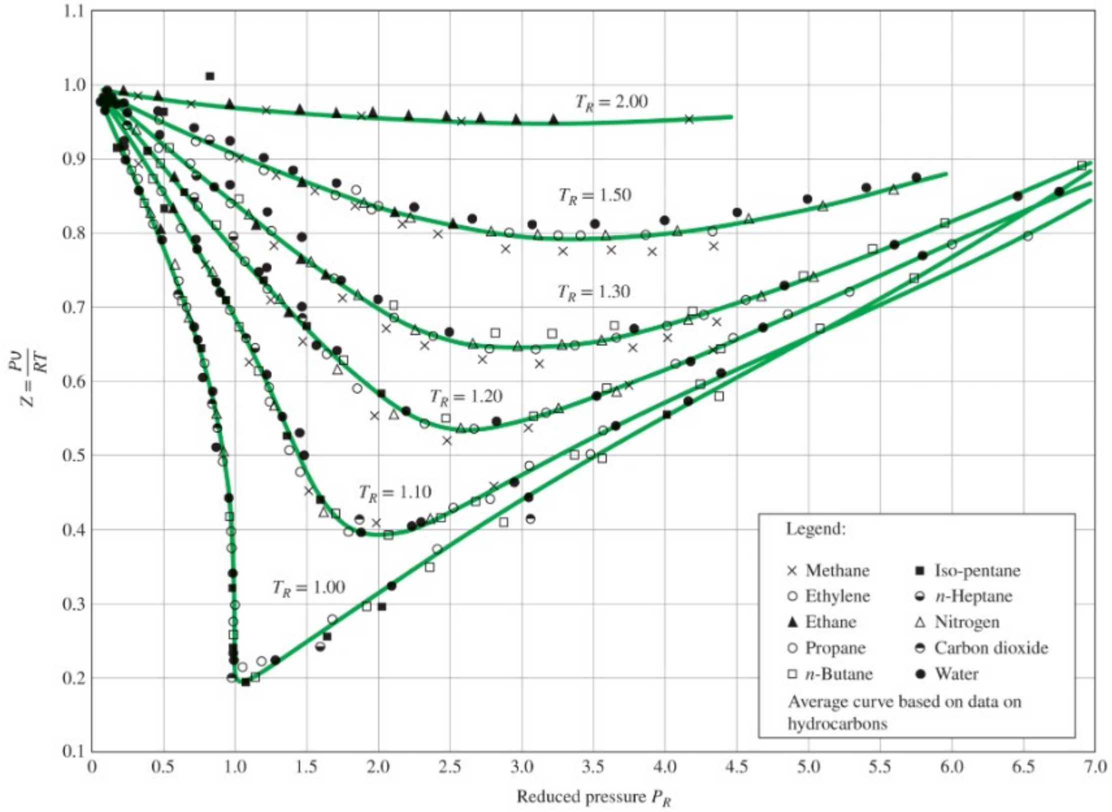
Compressibility Factor

- Generalized compressibility chart



Compressibility Factor

- A few observations:



CLASS ACTIVITY

Class Activity

- Determine specific volume of refrigeratnt-134a at 1 MPa and 50 °C using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m^3/kg and determine the error involved in each case.

Class Activity

- Solution (a):

TABLE A–1

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, M kg/kmol	Gas constant, R kJ/kg · K*	Critical-point properties Temperature, K	Pressure, MPa	Volume, m^3/kmol
Propane	C_3H_8	44.097	0.1885	370	4.26	0.1998
Propylene	C_3H_6	42.081	0.1976	365	4.62	0.1810
Sulfur dioxide	SO_2	64.063	0.1298	430.7	7.88	0.1217
Tetrafluoroethane (R-134a)	CF_3CH_2F	102.03	0.08149	374.2	4.059	0.1993
Trichlorofluoromethane (R-11)	CCl_3F	137.37	0.06052	471.2	4.38	0.2478
Water	H_2O	18.015	0.4615	647.1	22.06	0.0560
Xenon	Xe	131.30	0.06332	289.8	5.88	0.1186

$$v = \frac{RT}{P} = \frac{\left(0.0815\,\frac{kJ}{kg.K}\right)(50 + 273.15\ K)}{1000\ kPa} = 0.026325\,\frac{m^3}{kg}$$

$$Error = \frac{0.026325 - 0.021796}{0.021796} = 0.208$$

Class Activity

- Solution (b):

$$P_R = \frac{P}{P_{cr}} = \frac{1\ MPa}{4.059\ MPa} = 0.246$$

$$Z = 0.84$$

$$T_R = \frac{T}{T_{cr}} = \frac{323\ K}{374.2\ K} = 0.863$$

$$v_{actual} = Zv_{ideal} = (0.84)\left(0.026325\,\frac{m^3}{kg}\right) = 0.022113\,\frac{m^3}{kg}$$

$$Error = \frac{0.022113 - 0.021796}{0.021796} \sim 0.02$$