CAE 208 / MMAE 320: Thermodynamics

Fall 2023

September 28, 2023

Properties of Pure Substances (4)

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ANNOUNCEMENTS

Announcements

- Assignment 4 is due tonight
  - ❑ Please submit one file only
  - ❑ Always look at the solutions posted
- Assignment 5 will be posted next Tuesday
- Midterm is scheduled for October 10

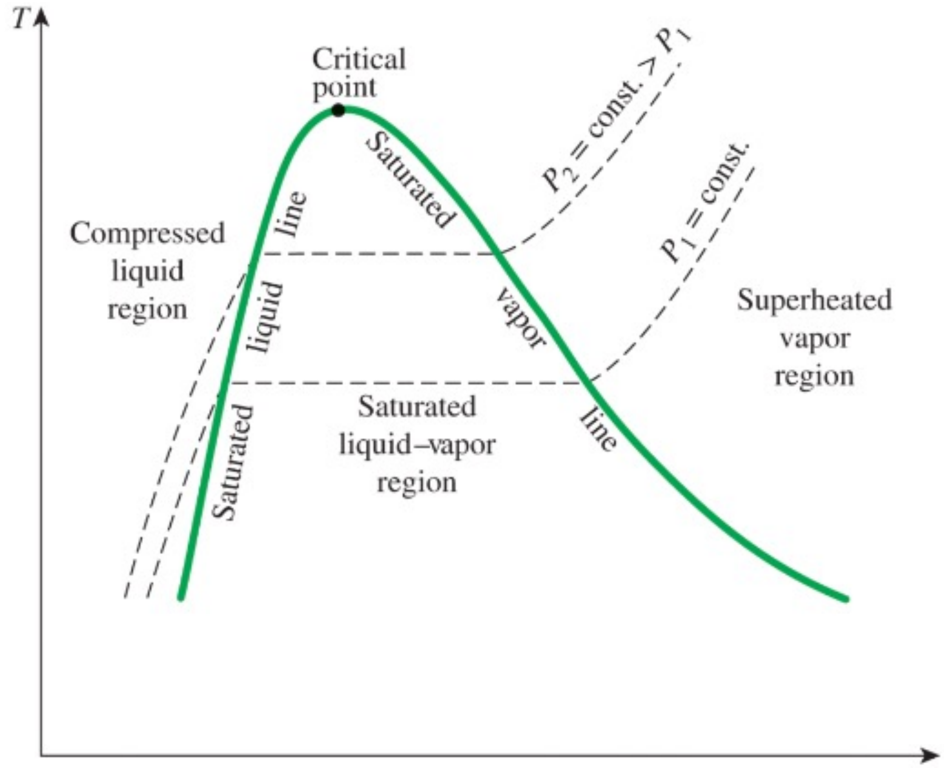
Announcements

- Starting next week, I will gradually introduce the bonus parts for working with coding or the hands-on activity

RECAP

Recap

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



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

- Could you show on the T-v or P-v diagram when do we use each table?

Recap

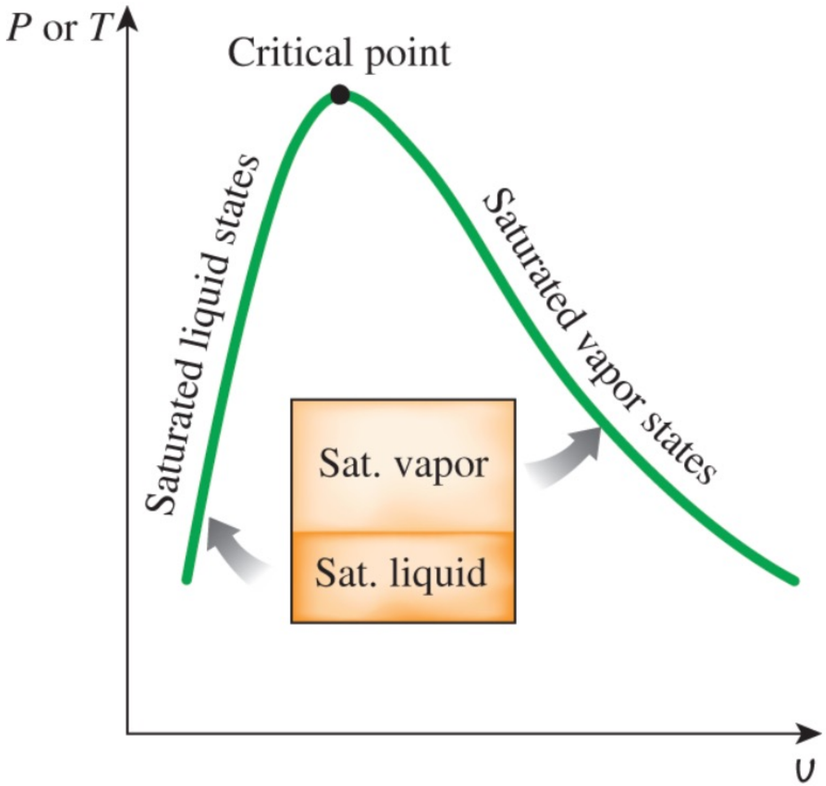
- If specific volume or enthalpy is given, how do we determine if the substance is a compressed liquid, saturated liquid, saturated liquid-vapor mixture, saturated vapor, or super heated?

Recap

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

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

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



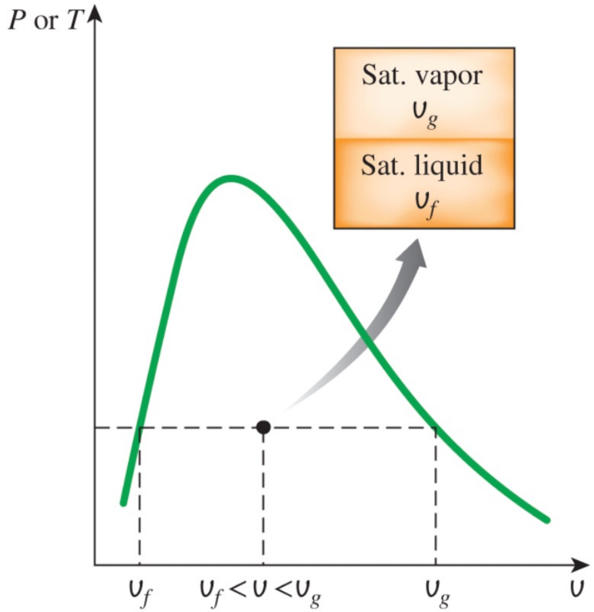
Recap

- We can write:

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

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

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



CLASS ACTIVITY

Class Activity

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

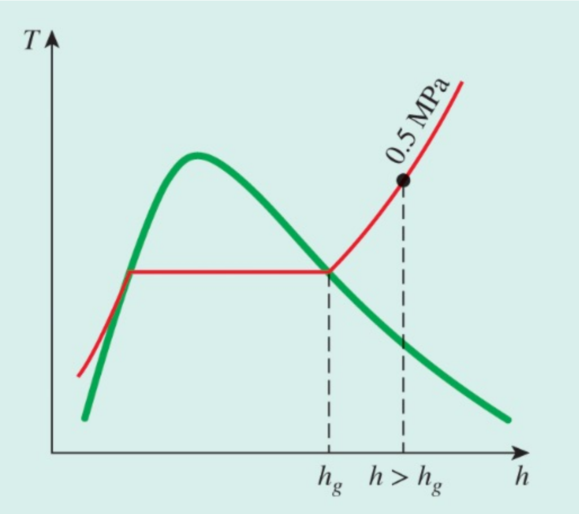
Class Activity

- Solution:

TABLE A–5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/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

Class Activity

- Solution:

$T(°C)$	$h(\frac{kJ}{kg})$
200	2,855.8
T	2,890
250	2,961.0

$$y = mx + b$$

$$h = mT + b$$

$$m = \frac{\Delta y}{\Delta x} = \frac{\Delta h}{\Delta T} = \frac{2{,}961.0 - 2{,}855.8}{250 - 200} = 2.12$$

Class Activity

- Solution:

$T(°C)$	$h(\frac{kJ}{kg})$
200	2,855.8
T	2,890
250	2,961.0

$$h = mT + b$$

$$@T = 200\,°C \;\rightarrow h = 2{,}855.8 = 2.12(200) + b \;\rightarrow b = 2{,}431.8$$

$$h = 2.12T + 2431.8$$

$$h = 2{,}890\,\frac{kJ}{kg} = 2.12T + 2431.8 \;\rightarrow T = 216.3\,°C$$

Superheated Vapor

- Compared to the saturated vapor, superheated vapor is characterized by

Lower pressures ($P < P_{sat}$ at a given T)

Higher temperatures ($T > T_{sat}$ at a given P)

Higher specific volumes ($v > v_g$ at a given P or T)

Higher internal energies ($u > u_g$ at a given P or T)

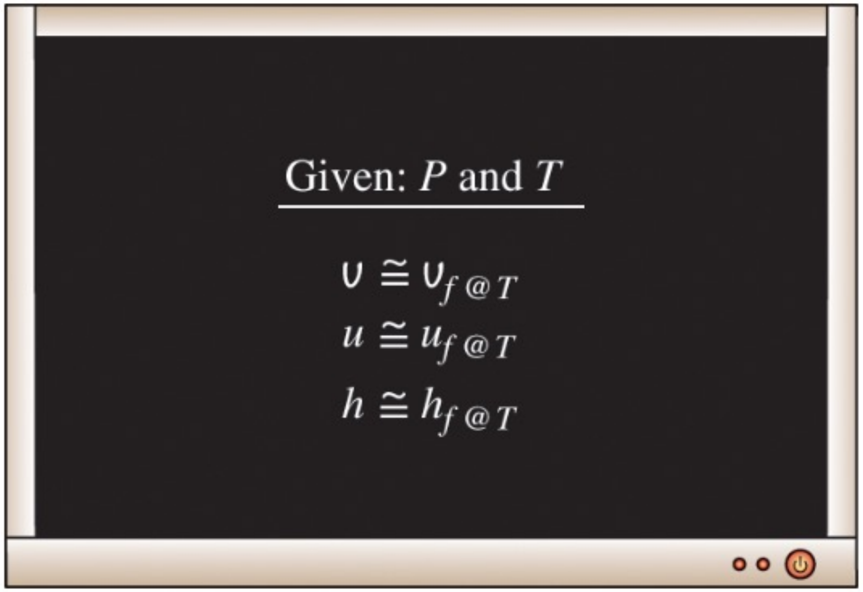
Higher enthalpies ($h > h_g$ at a given P or T)

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)

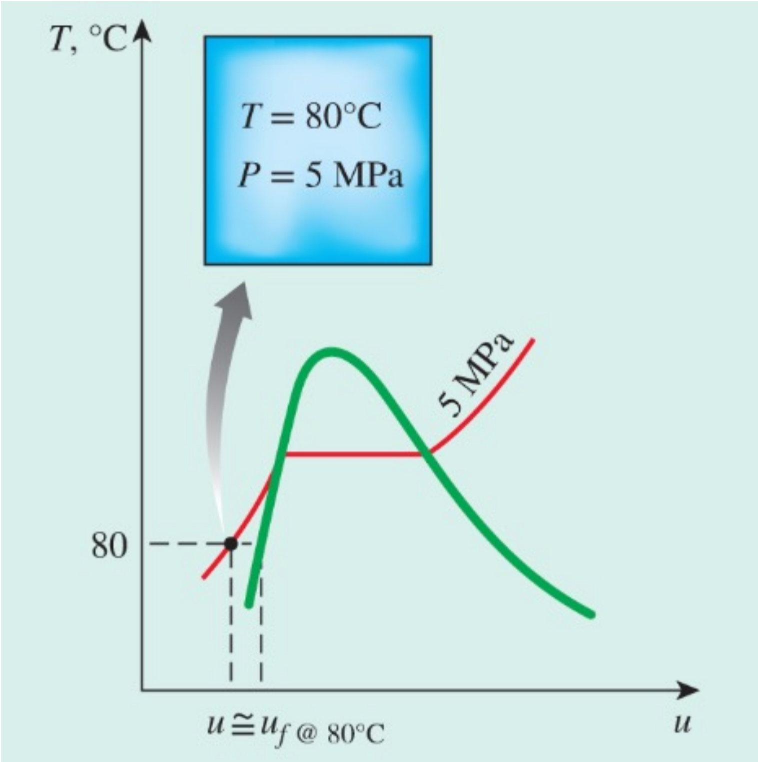
CLASS ACTIVITY

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, 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
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:

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

QUIZ

Quiz

Quiz

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:

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

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

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

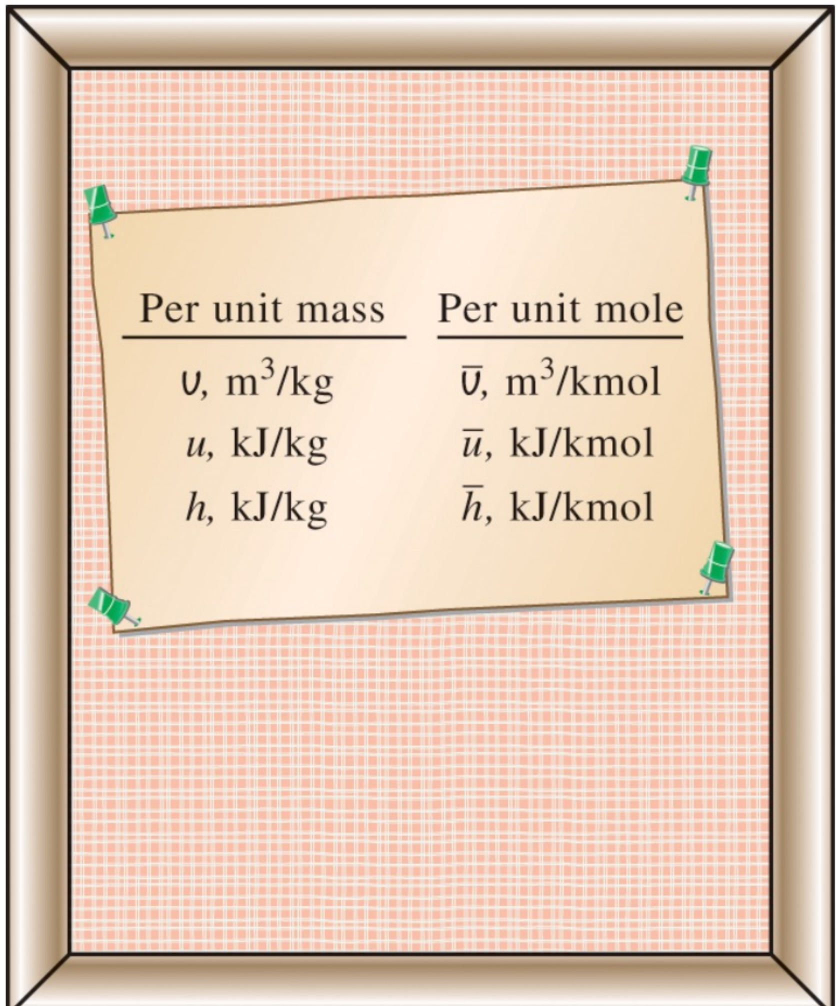
$$PV = (NM)RT$$

$$PV = NR_uT$$

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

The Ideal-Gas Equation of State

- Properties per unit mole are:



The Ideal-Gas Equation of State

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

$$PV = mRT$$

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

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?

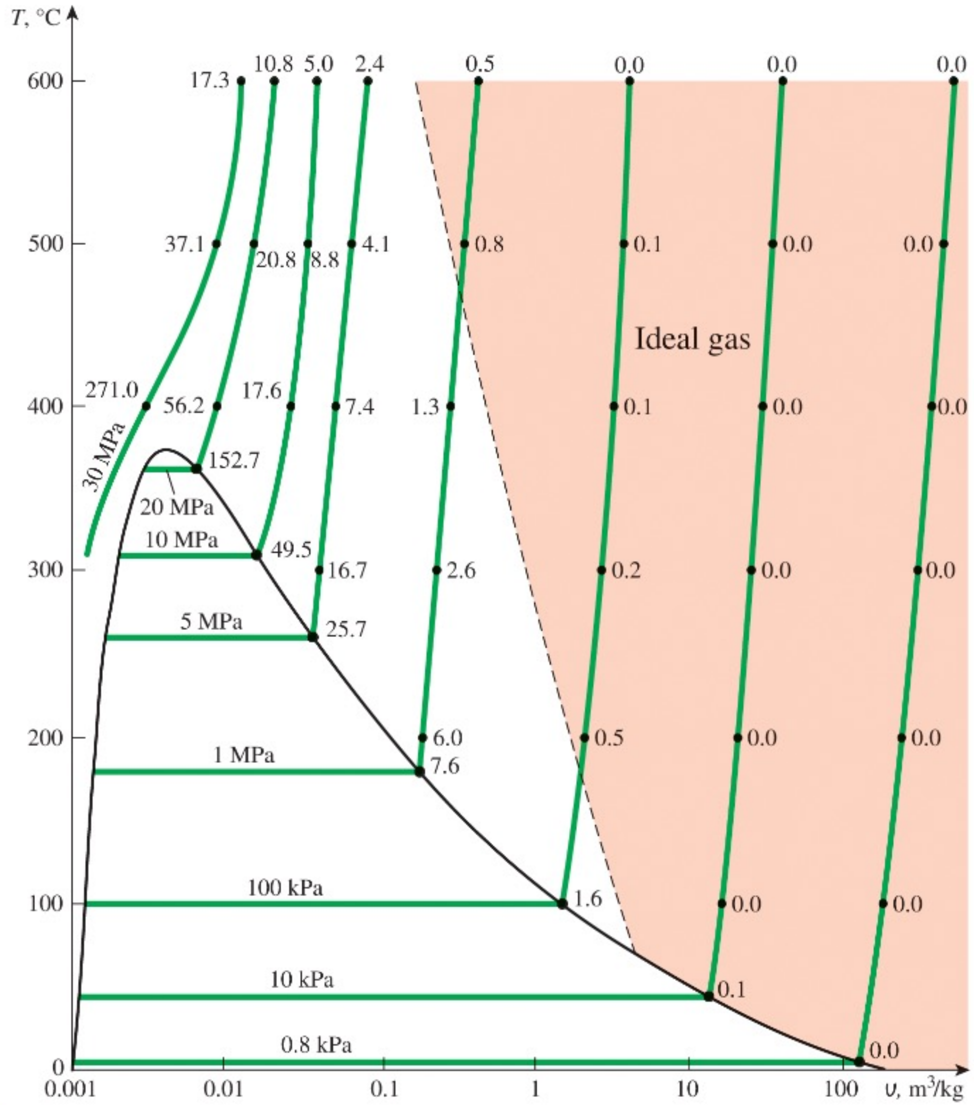


FIGURE 4–46

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

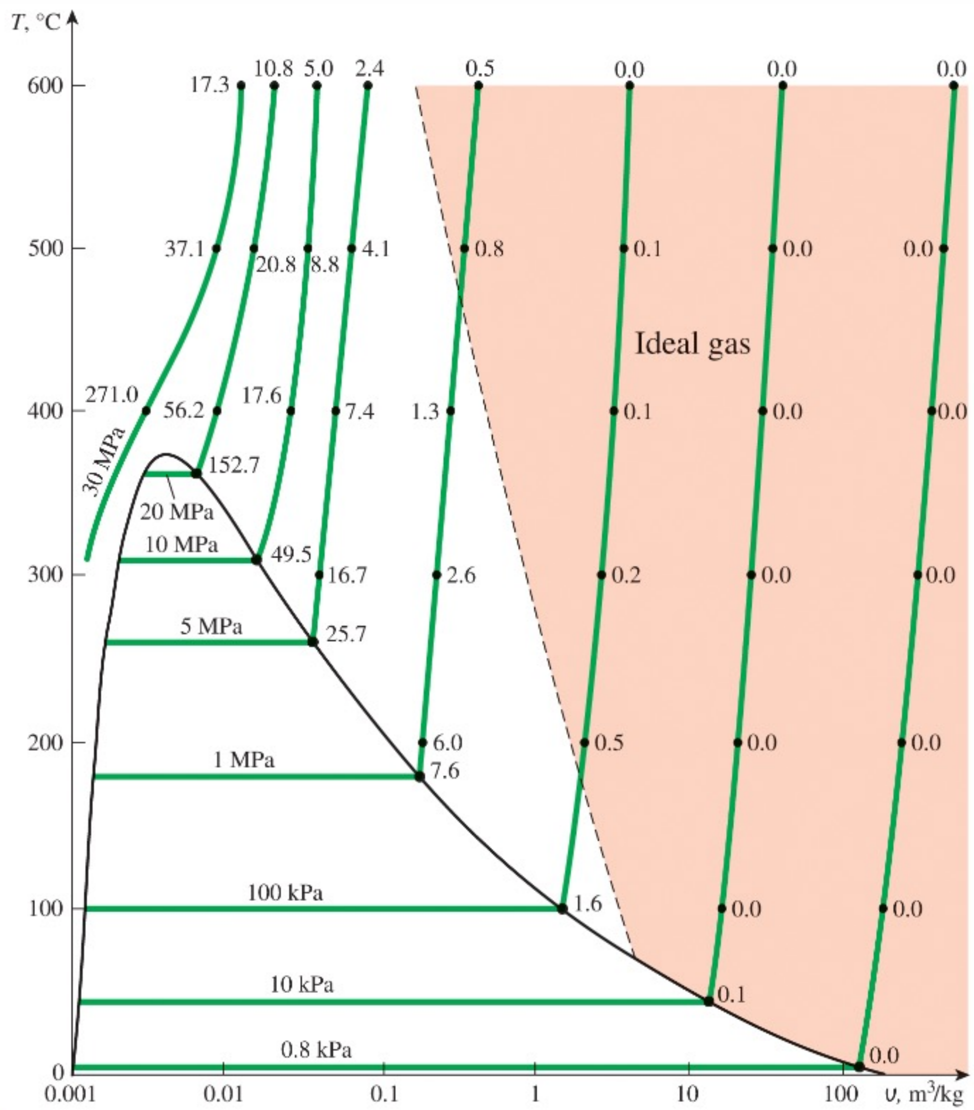


FIGURE 4–46

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

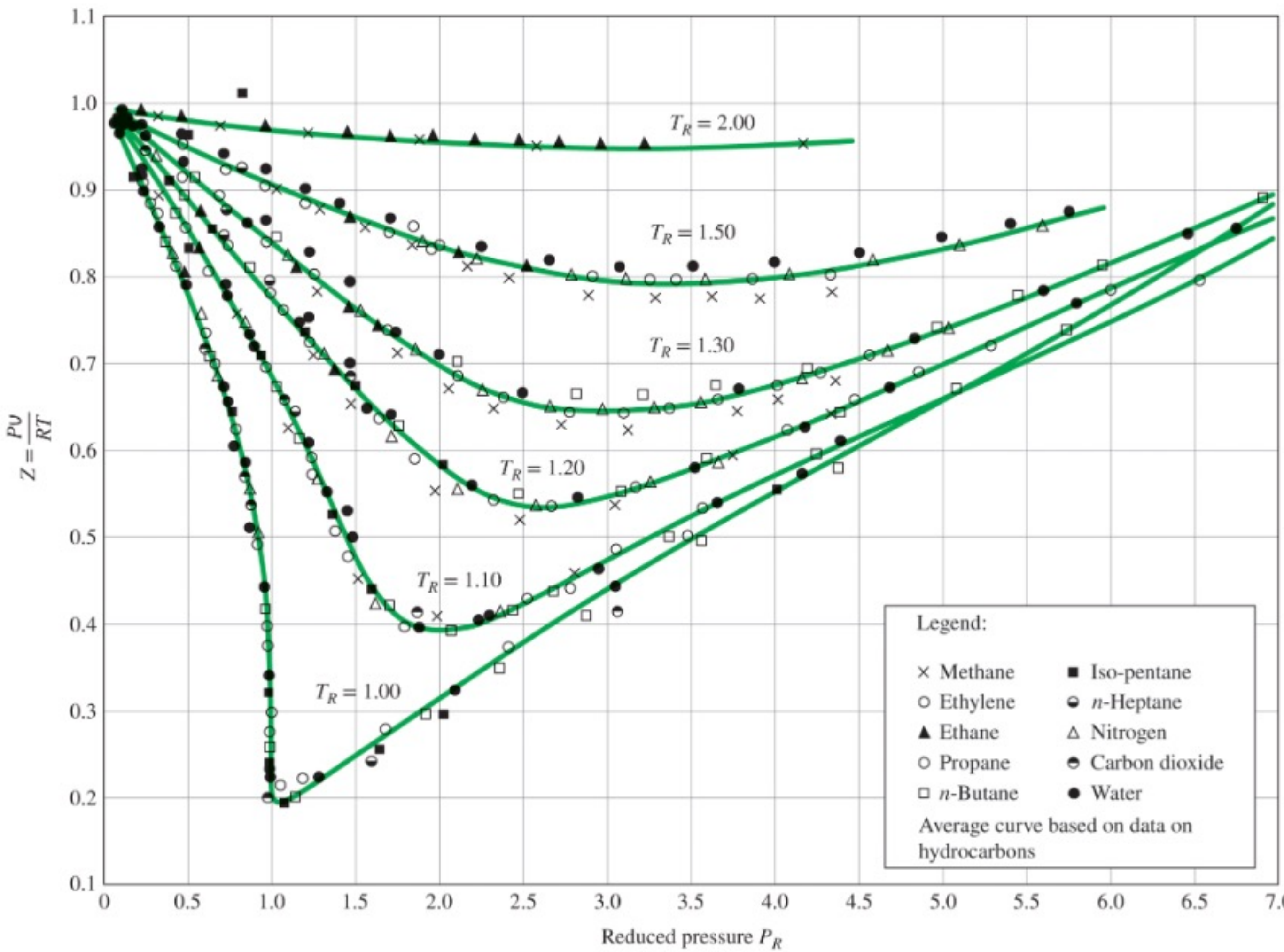
- Z factor for all gases is approximately the same at the same reduced temperature and pressure due to the principle of corresponding states

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

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

Compressibility Factor

- We can define a “generalized compressibility chart”
- Let’s look at 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):

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

$$Z = 0.84$$

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

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

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

CLASS ACTIVITY

Class Activity

- Determine the specific volume of refrigerant-134a vapor at 0.9 MPa and 70°C based on
  a) The ideal-gas equation
  b) The generalized compressibility chart
  c) Data from tables. Also, determine the error involved in the first two cases.

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

$$R = 0.08149 \frac{kJ}{kg - K}$$

$$T_{cr} = 374.2\ K$$

$$P_{cr} = 4.049\ MPa$$

Class Activity

- Solution (a):

$$Pv = RT$$

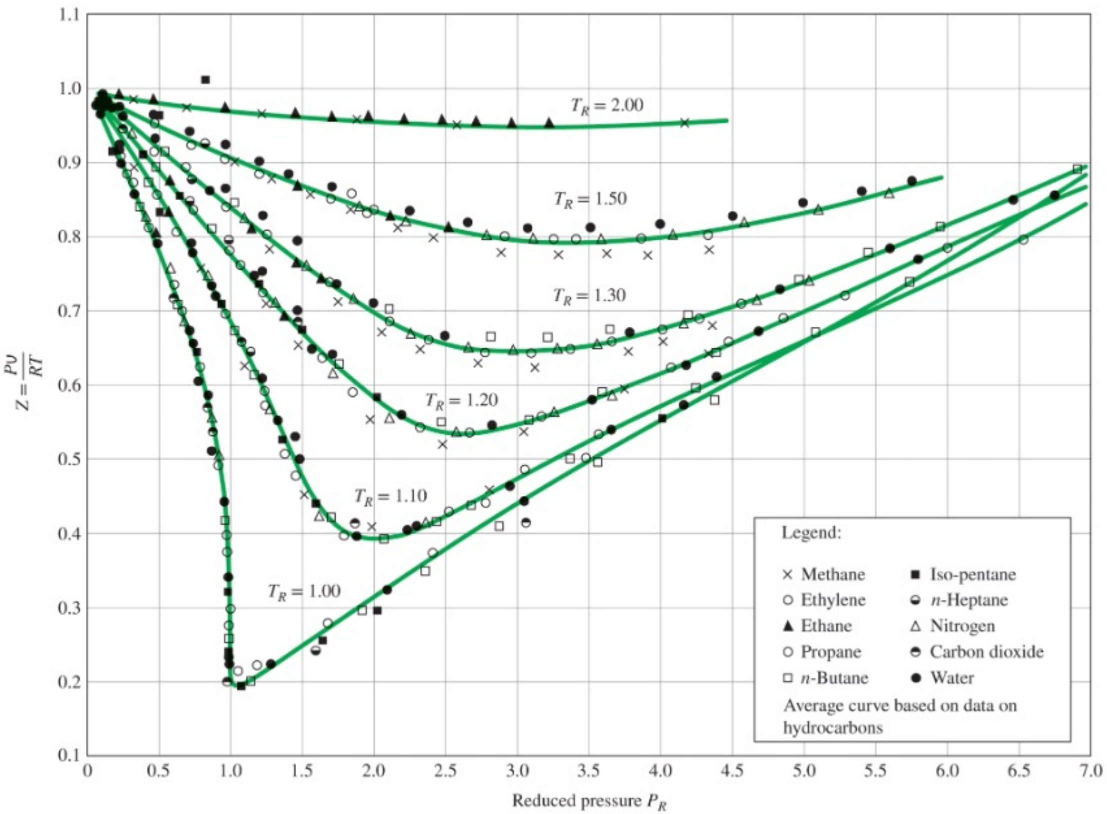
$$v = \frac{RT}{P} = \frac{(0.08149\,\frac{kJ}{kg-K})(273.15 + 70\ K)}{0.9\times10^{3}\ kPa} = 0.03105\,\frac{m^3}{kg}$$

Class Activity

- Solution (b):

$$P_R = \frac{P}{P_{cr}} = \frac{0.9}{4.049} = 0.222$$

$$T_R = \frac{T}{T_{cr}} = \frac{343}{374.2} = 0.917$$



$$Z = 0.894$$

Class Activity

- Solution (b):

$$v = Zv_{ideal} = (0.894)\left(0.03105\,\frac{m^3}{kg}\right) = 0.02776\,\frac{m^3}{kg}$$

Class Activity

- Solution (c):

TABLE A–13

Superheated refrigerant-134a

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
	$P = 0.80$ MPa ($T_{sat} = 31.31$°C)				$P = 0.90$ MPa ($T_{sat} = 35.51$°C)			
Sat.	0.025645	246.82	267.34	0.9185	0.022686	248.82	269.25	0.9169
40	0.027035	254.84	276.46	0.9481	0.023375	253.15	274.19	0.9328
50	0.028547	263.87	286.71	0.9803	0.024809	262.46	284.79	0.9661
60	0.029973	272.85	296.82	1.0111	0.026146	271.62	295.15	0.9977
70	0.031340	281.83	306.90	1.0409	0.027413	280.74	305.41	1.0280
80	0.032659	290.86	316.99	1.0699	0.028630	289.88	315.65	1.0574
90	0.033941	299.97	327.12	1.0982	0.029806	299.08	325.90	1.0861