CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics
Fall 2022

September 29, 2022
Properties of Pure Substances (IV)

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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

Last updated September 29, 2022

Course Topics and Tentative Schedule

Week	Date	Topics	Reading	Assignment Due
1	08/23/22	Introduction and Overview (I)	Ch. 1	
	08/25/22	Basic Concepts of Thermodynamics (I)	Ch. 2	
2	08/30/22	Basic Concepts of Thermodynamics (II)	Ch. 2	
	09/01/22	Basic Concepts of Thermodynamics (III)	Ch. 2	
3	09/06/22	Energy, Energy Transfer, and General Energy Analysis (I)	Ch. 3	Assignment 1
	09/08/22	Energy, Energy Transfer, and General Energy Analysis (II)	Ch. 3	
4	09/13/22	Properties of Pure Substances (I)	Ch. 4	Assignment 2
	09/15/22	No Class – Recording	Ch. 4	
5	09/20/22	Properties of Pure Substances (II)	Ch. 4	Assignment 3
	09/22/22	Properties of Pure Substances (III)	Ch. 4	
6	09/27/22	Properties of Pure Substances (IV)	Ch. 4	
	09/29/22	Energy Analysis of Closed Systems (I)	Ch. 5	Assignment 4
7	10/04/22	Energy Analysis of Closed Systems (II)	Ch. 5	
	10/06/22	Mass and Energy Analysis of Control Volumes (I)	Ch. 6	
8	10/11/22	Mass and Energy Analysis of Control Volumes (II)	Ch. 6	Assignment 5
	10/13/22	**Exam 1**		

Announcements

ASHRAE
Illinois Institute of Technology
Student Branch

HAB LAB

Simulating Buildings for a Living

SPEAKER

President/Founder
P.E., LEED AP BD+C **Graham Linn**

WHEN

September 29th, 2022
12:40pm – 1:40pm

WHERE

John T. Rettaliata Engineering Center, RE 124

TALK ABOUT

- ✓ Career Journey
- ✓ Career tips
- ✓ Technical Building Performance

For more information, feel free to contact ASHRAE official email ashrae_iit@iit.edu

Interested in Joining

Lunch will be provided!

Habitat

+

Laboratory

= HAB LAB

Announcements

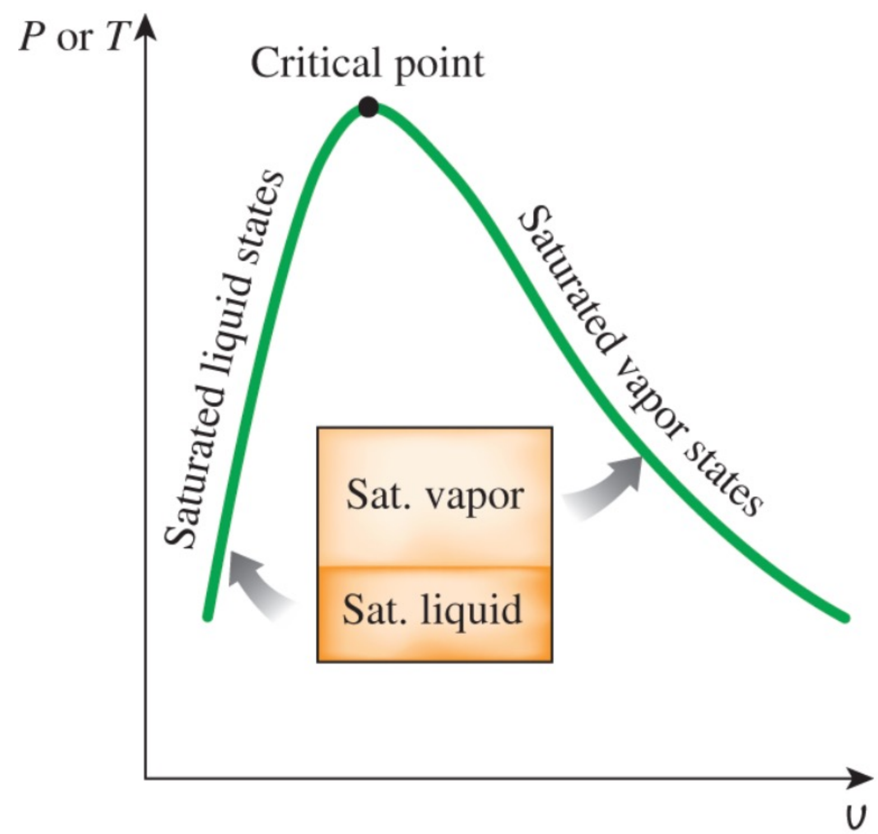
- Let's find a few potential times for the online problem-solving session?

RECAP

Recap

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

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



Recap

- 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)

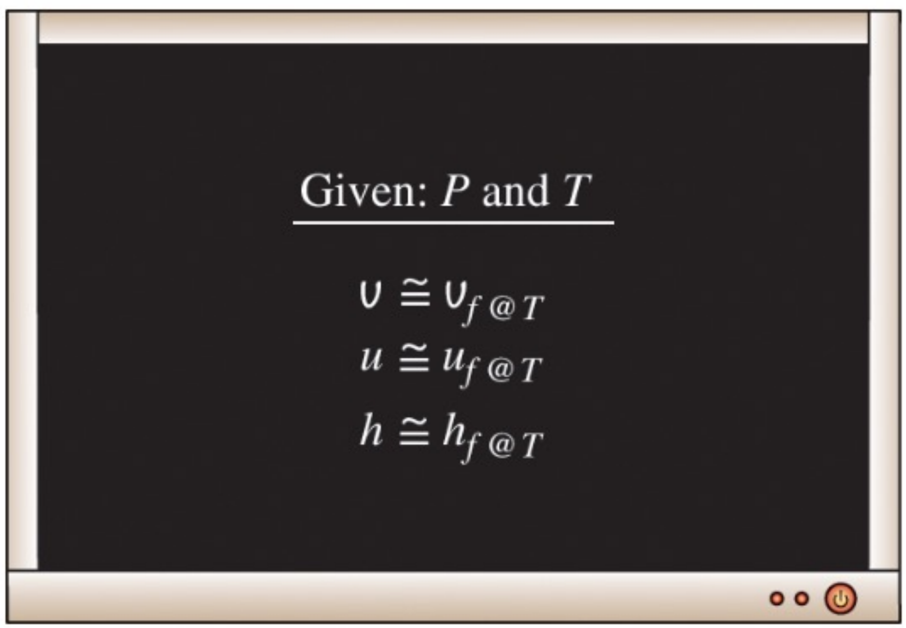
Higher internal energies ($u > u_g$ at a given P or T)

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

Recap

- 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



Recap

- 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)

Recap

- Sometimes interpolation is needed

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

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 are 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 (assuming the intermolecular attraction between molecules is zero).

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

$$Pv = RT$$

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 mass of kmol in kilograms
  - ❑ Or, the mass of 1 lbmol in lbm

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

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

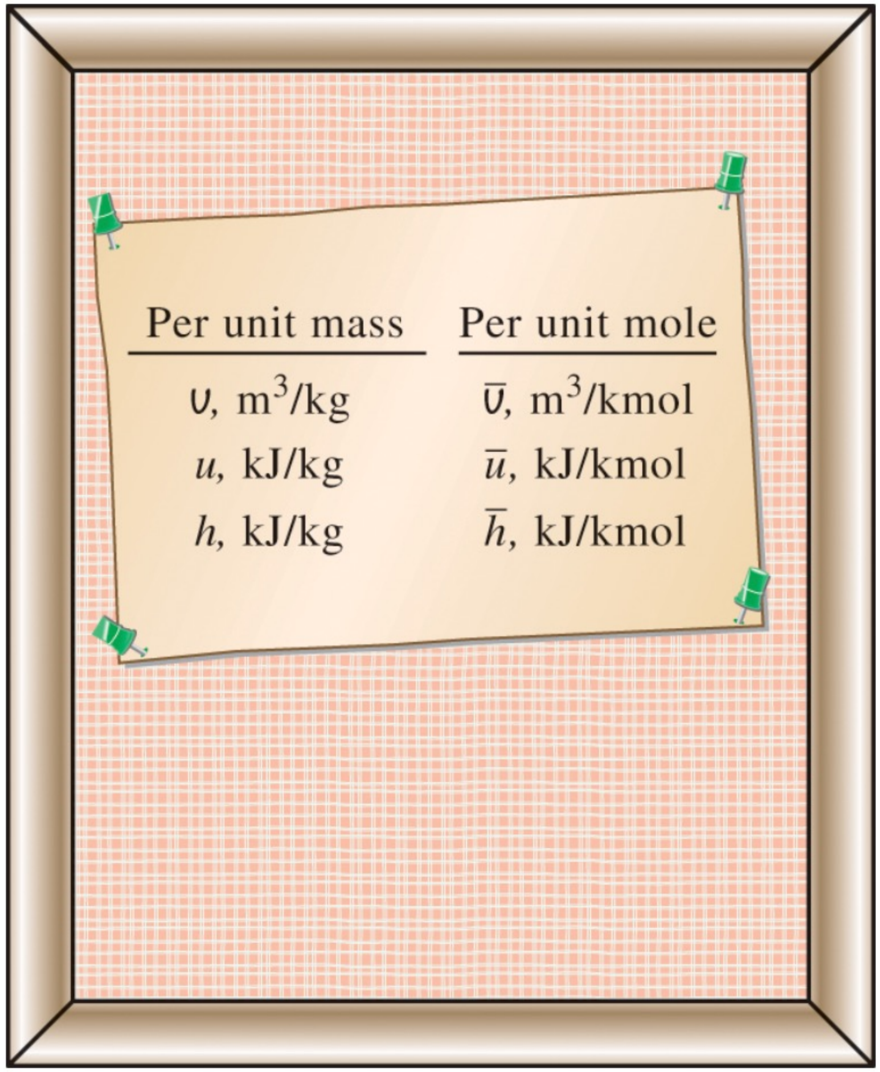
$$PV = (NM)RT$$

$$PV = NR_uT$$

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

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:

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

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?

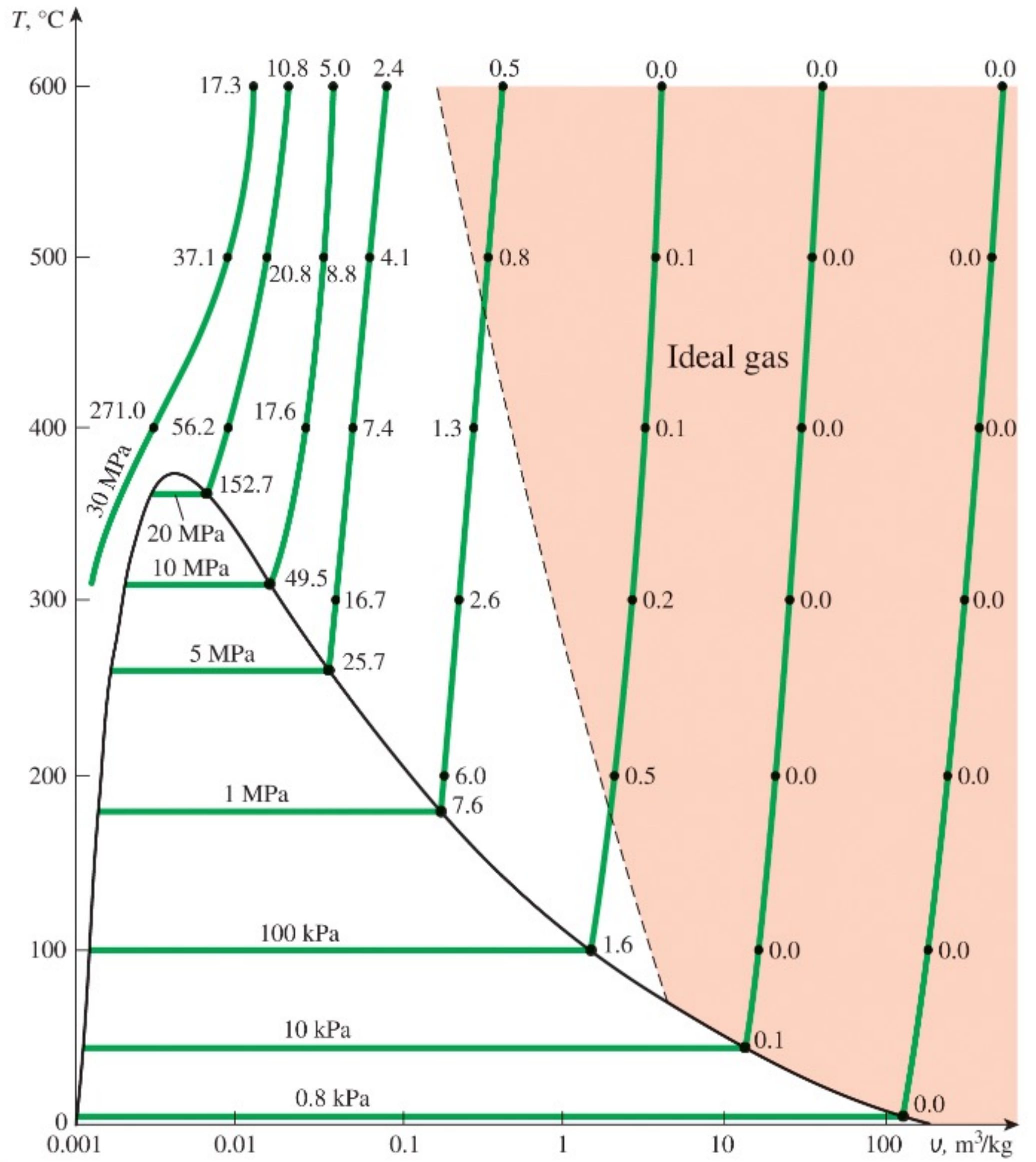


FIGURE 4–46

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

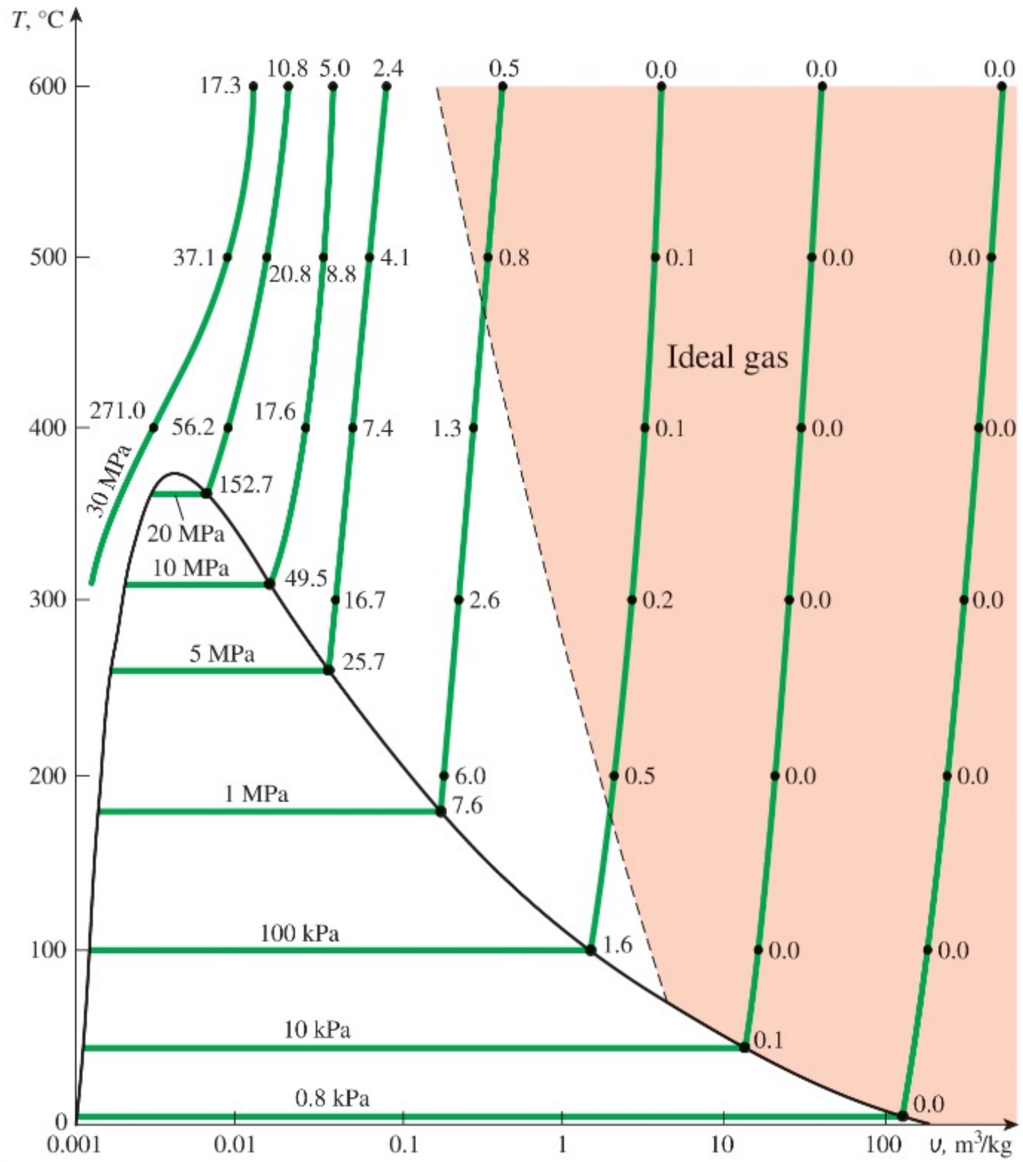


FIGURE 4–46

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

$$Z = \frac{Pv}{RT}$$

$$Pv = ZRT$$

$$Z = \frac{v_{actual}}{v_{ideal}}$$

Compressibility Factor

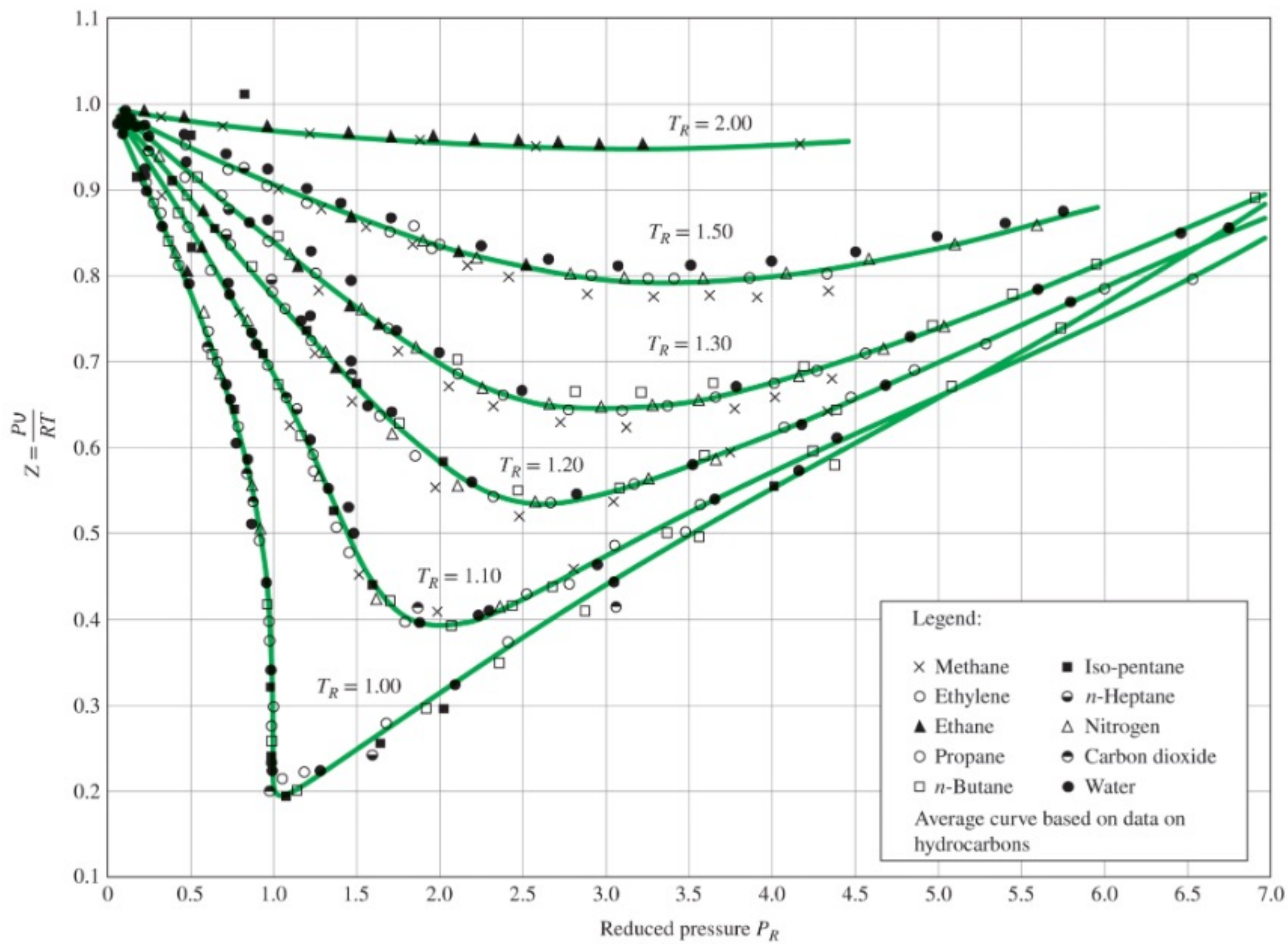
- We can define reduced pressure and reduced temperature
- This is based on the principle of corresponding states

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

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

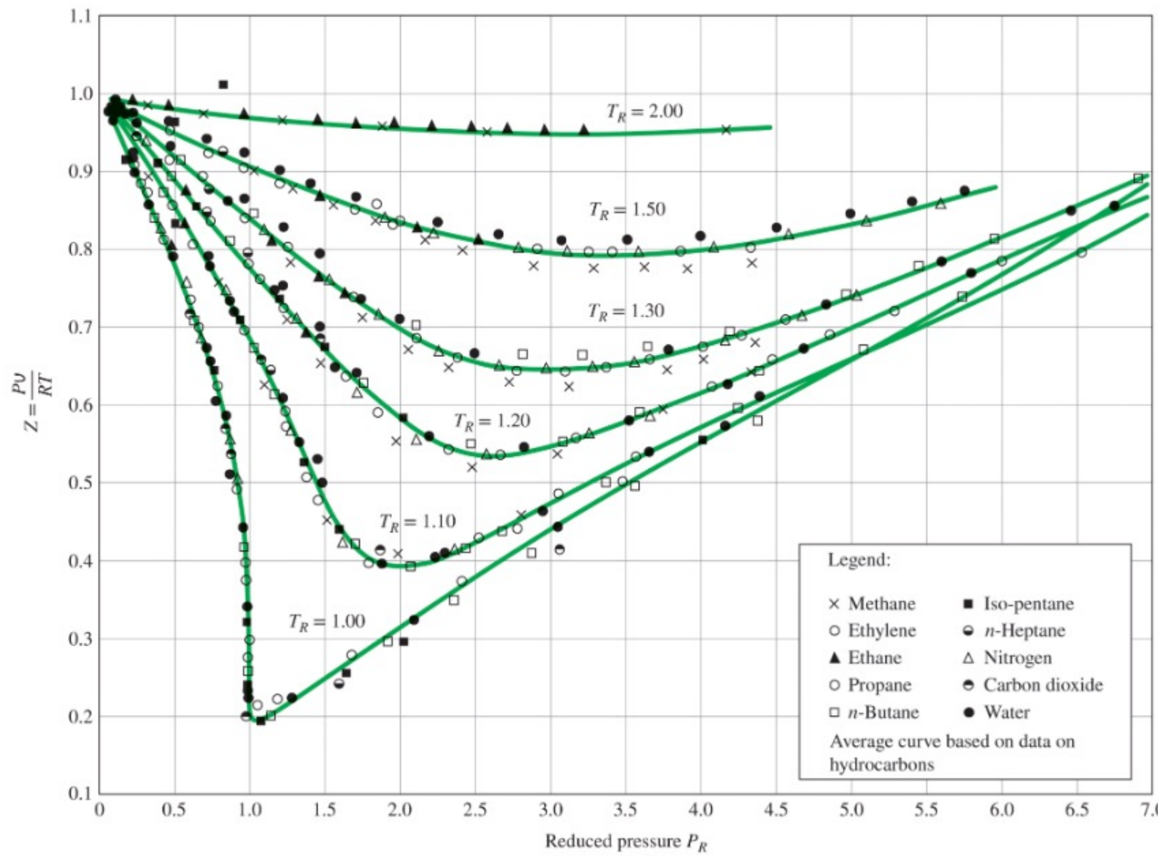
Compressibility Factor

- 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):

$$\begin{cases} P_R = \dfrac{P}{P_{cr}} = \dfrac{1\ MPa}{4.059\ MPa} = 0.246 \\ \\ T_R = \dfrac{T}{T_{cr}} = \dfrac{323\ K}{374.2\ K} = 0.863 \end{cases}$$

$$Z = 0.84$$

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

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

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
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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):

$$Pv = RT$$

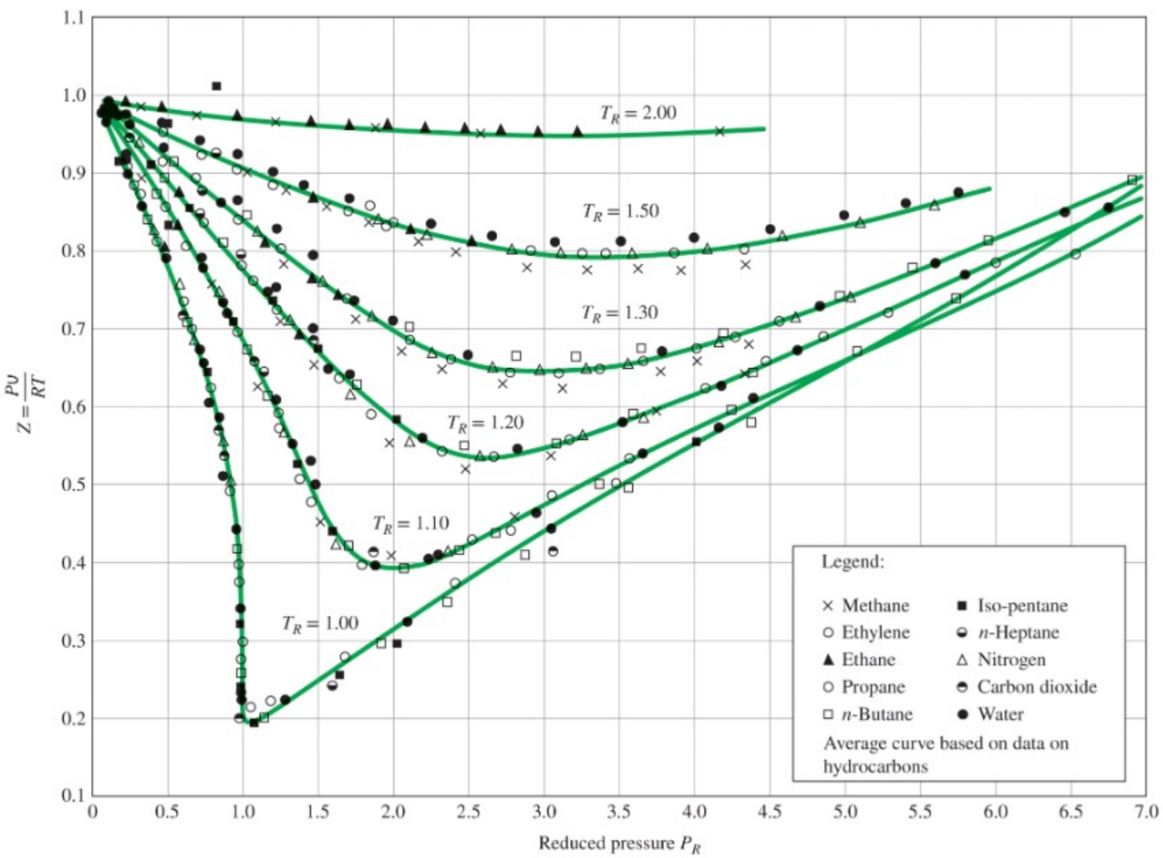
$$v = \frac{RT}{P} = \frac{(0.08149\,\frac{kJ}{kg-K})(273.15 + 70\ K)}{0.9{\times}10^3\ kPa} = 0.03105\,\frac{m^3}{kg}$$

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