

Thermodynamics: An Engineering Approach

8th Edition

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CHAPTER 3

PROPERTIES OF PURE SUBSTANCES

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Objectives

- Introduce the concept of a pure substance
- Discuss the physics of phase-change processes
- Illustrate the P - v , T - v , and P - T property diagrams and P - v - T surfaces of pure substances
- Obtaining thermodynamic properties of pure substances from tables of property data
- Describe “ideal gas” and the ideal-gas equation of state and demonstrate its use
- Introduce the compressibility factor, which accounts for the deviation of real gases from ideal-gas behavior
- Present some of the commonly used equations of state

PURE SUBSTANCE

- **Pure substance:** is the one that has a homogeneous and invariable chemical composition i.e. a pure substance has a fixed chemical composition throughout
- Air is a mixture of several gases, but it is considered to be a pure substance as its chemical composition is fixed

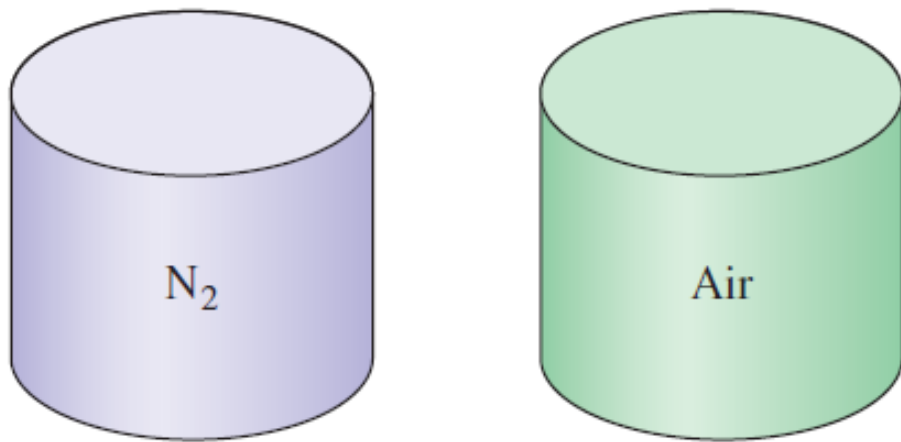
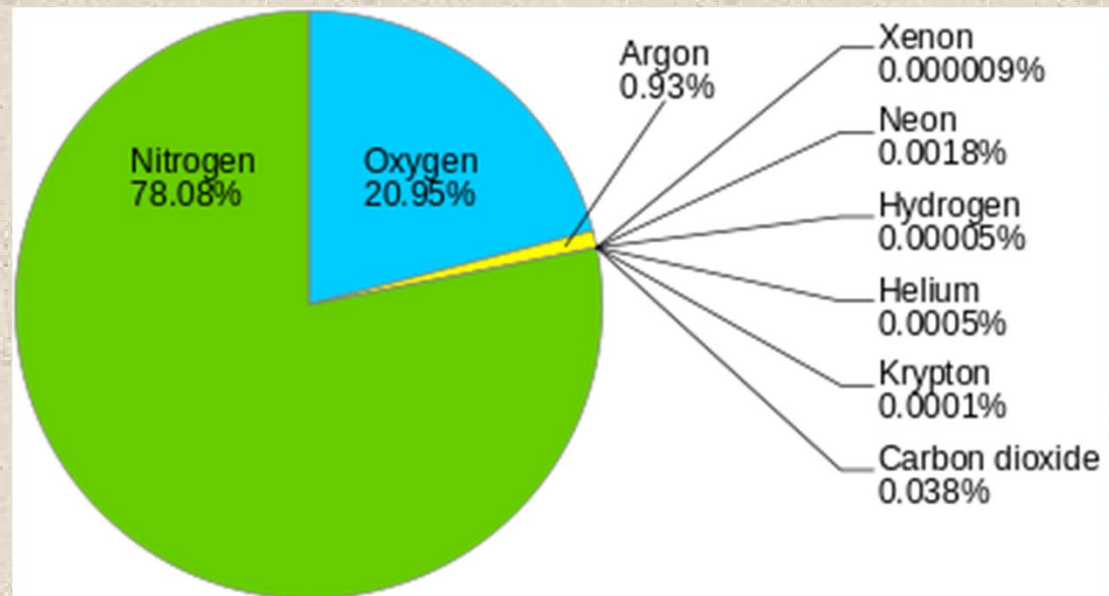


FIGURE 3–1

Nitrogen and gaseous air are pure substances.



www.wikipedia.org

PURE SUBSTANCE IN MULTIPLE PHASES

- Pure substance may exist in more than one phase, but the *chemical composition is same in all phases*
- Thus, liquid water, a mixture of liquid water and water vapor (steam), and a mixture of ice and liquid water are all pure substances; every phase has the same chemical composition
- Mixture of air and liquid air is not a pure substance, since the relative proportions of oxygen and nitrogen differ in gas and liquid phases in equilibrium

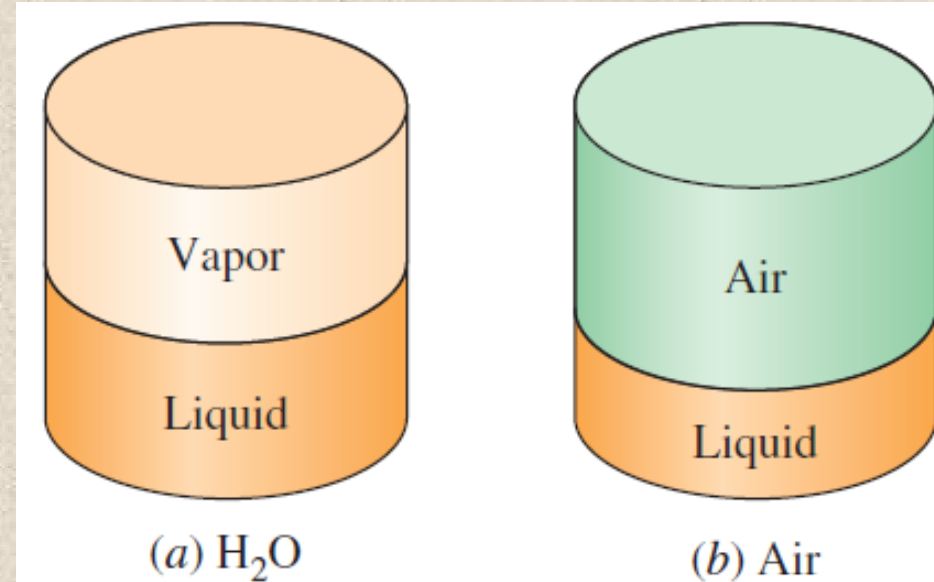


FIGURE 3–2

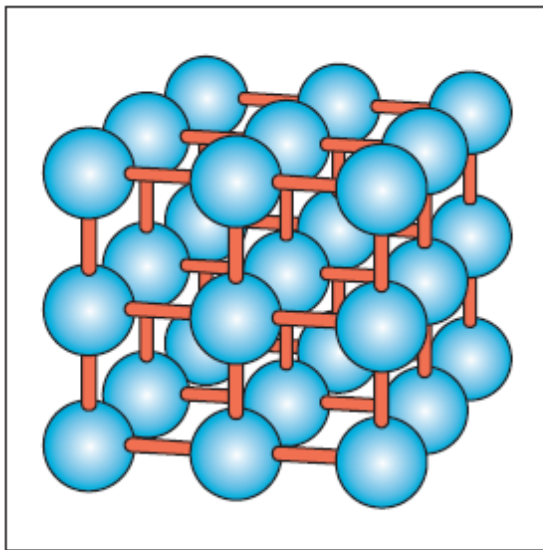
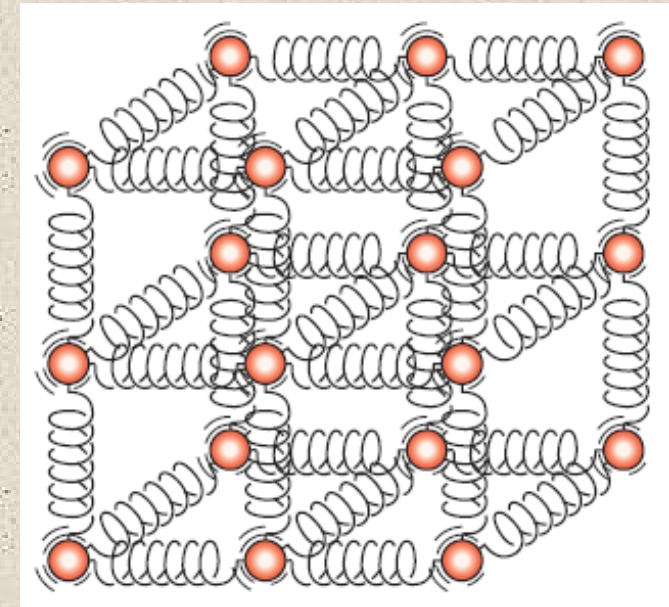
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

Boiling point O₂ (P = 1 atm): 90 K

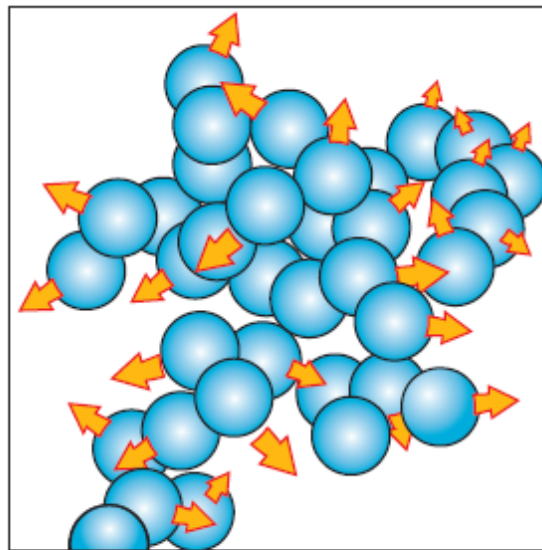
Boiling point N₂ (P = 1 atm): 77 K

PHASES OF A PURE SUBSTANCE

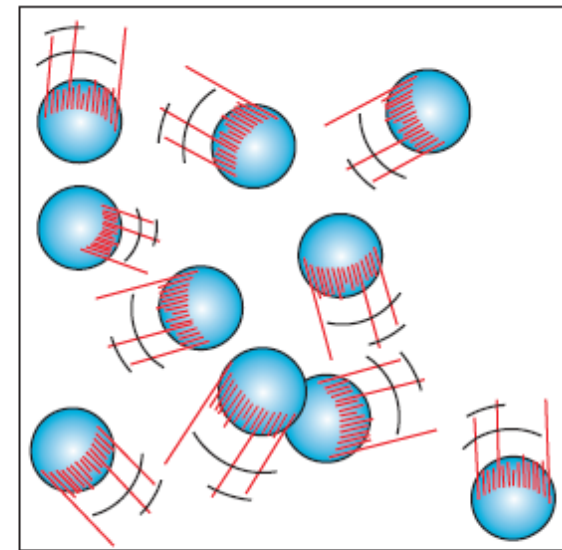
- The molecules in a solid are kept at their positions by the large spring like inter-molecular forces
- Molecules in liquid glide past each other
- Molecules in gases move freely



(a)



(b)



(c)

FIGURE 3-4

The arrangement of atoms in different phases: (a) molecules are at relatively fixed positions in a solid, (b) groups of molecules move about each other in the liquid phase, and (c) molecules move about at random in the gas phase.

PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

Compressed liquid (subcooled liquid): A substance that it is *not about to vaporize*

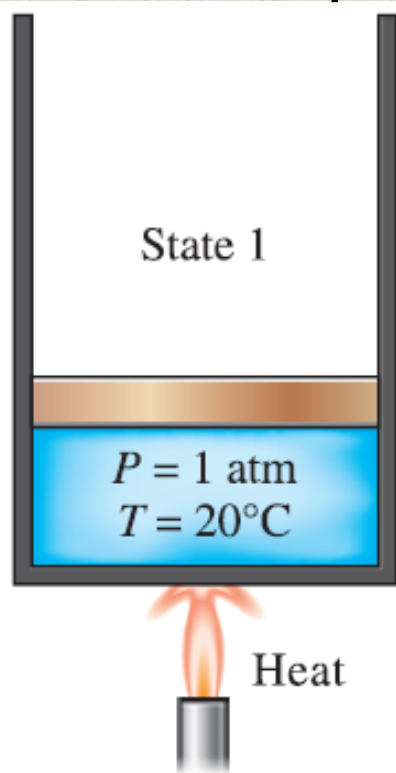


FIGURE 3–5

At 1 atm and 20°C , water exists in the liquid phase (*compressed liquid*).

Saturated liquid: A liquid that is *about to vaporize*

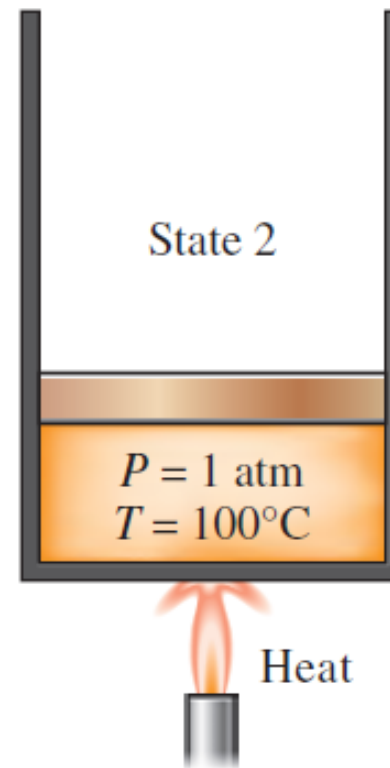
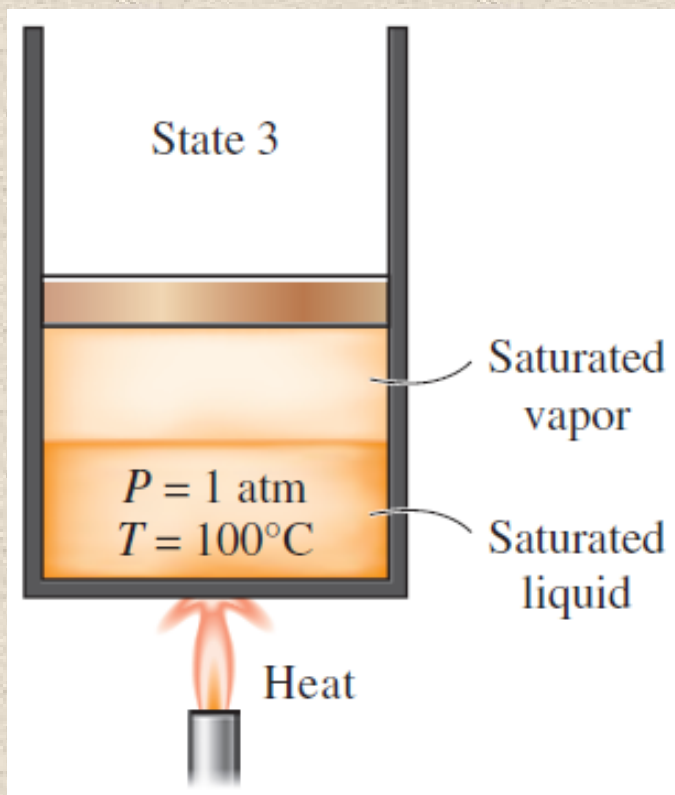


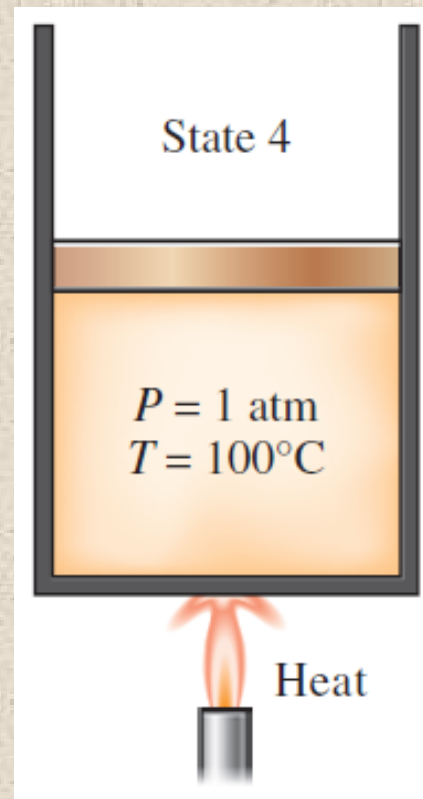
FIGURE 3–6

At 1 atm pressure and 100°C , water exists as a liquid that is ready to vaporize (*saturated liquid*).

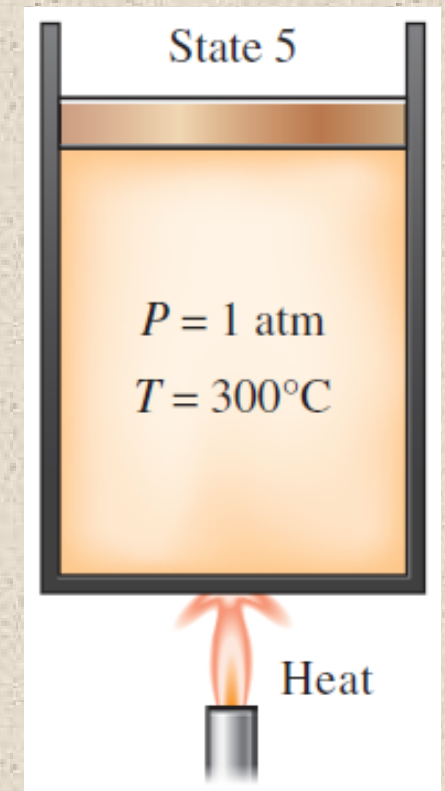
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium
- **Saturated vapor**: A vapor that is *about to condense*
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor)



As more heat is transferred, part of the saturated liquid vaporizes (**saturated liquid–vapor mixture**)

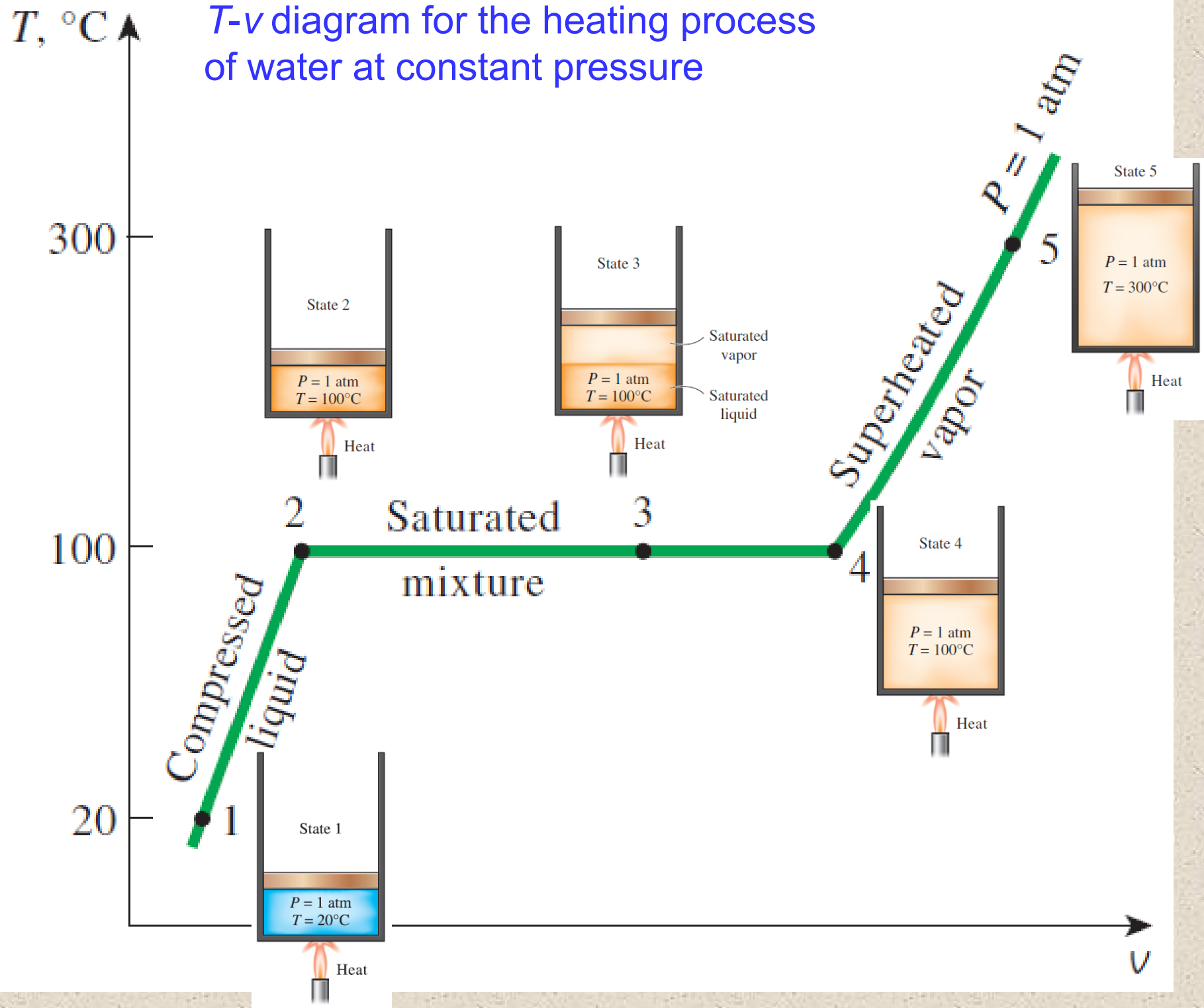


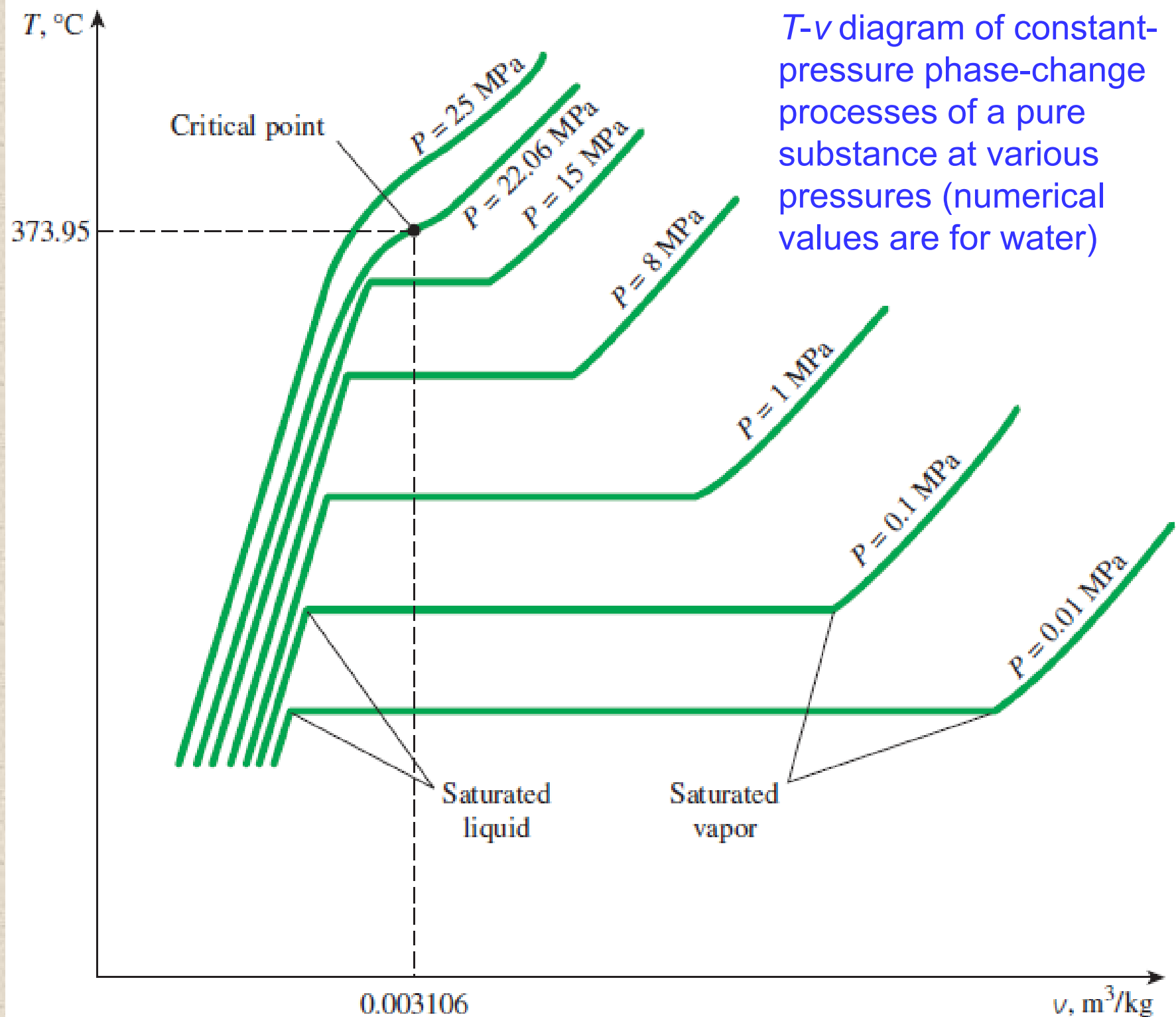
At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (**saturated vapor**)



As more heat is transferred, the temperature of the vapor starts to rise (**superheated vapor**).

T - v diagram for the heating process of water at constant pressure





Boiling Point

- The temperature at which water starts boiling depends on the pressure
- Water boils at 100°C at 1 atm and at 150 °C at 4.7 atm*

TABLE 3–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

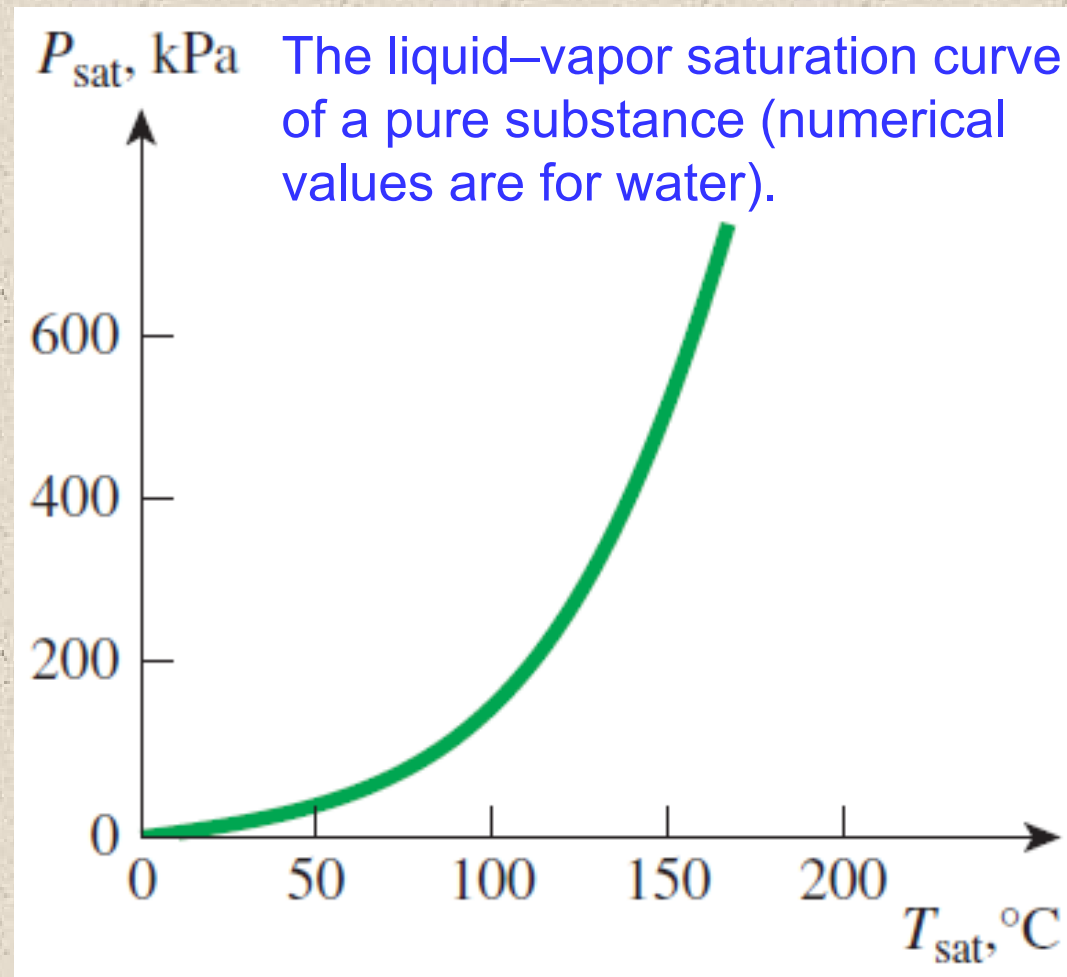
Leh,
Ladakh:
3,500 m

TABLE 3–1

Saturation (or vapor) pressure of water at various temperatures

Temperature $T, ^\circ\text{C}$	Saturation Pressure $P_{\text{sat}}, \text{kPa}$
–10	0.260
–5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Saturation Temperature and Saturation Pressure



- **Saturation temperature T_{sat}** : The temperature at which a pure substance changes phase *at a given pressure*
- **Saturation pressure P_{sat}** : The pressure at which a pure substance changes phase *at a given temperature*

Some Consequences of T_{sat} and P_{sat} Dependence

- Boiling temperature of nitrogen at atmospheric pressure is -196°C

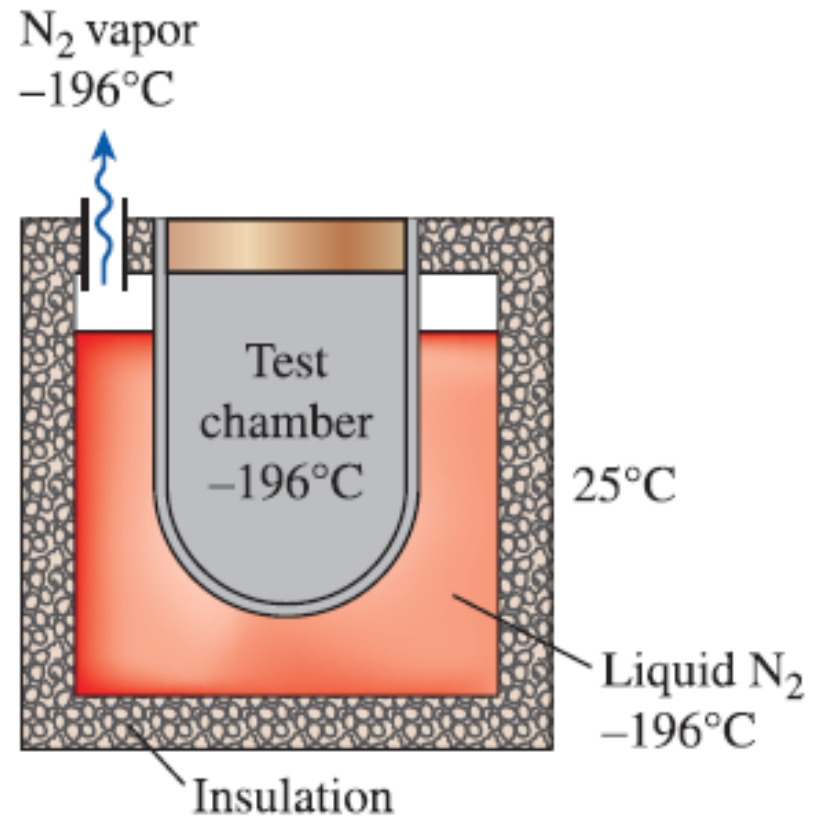
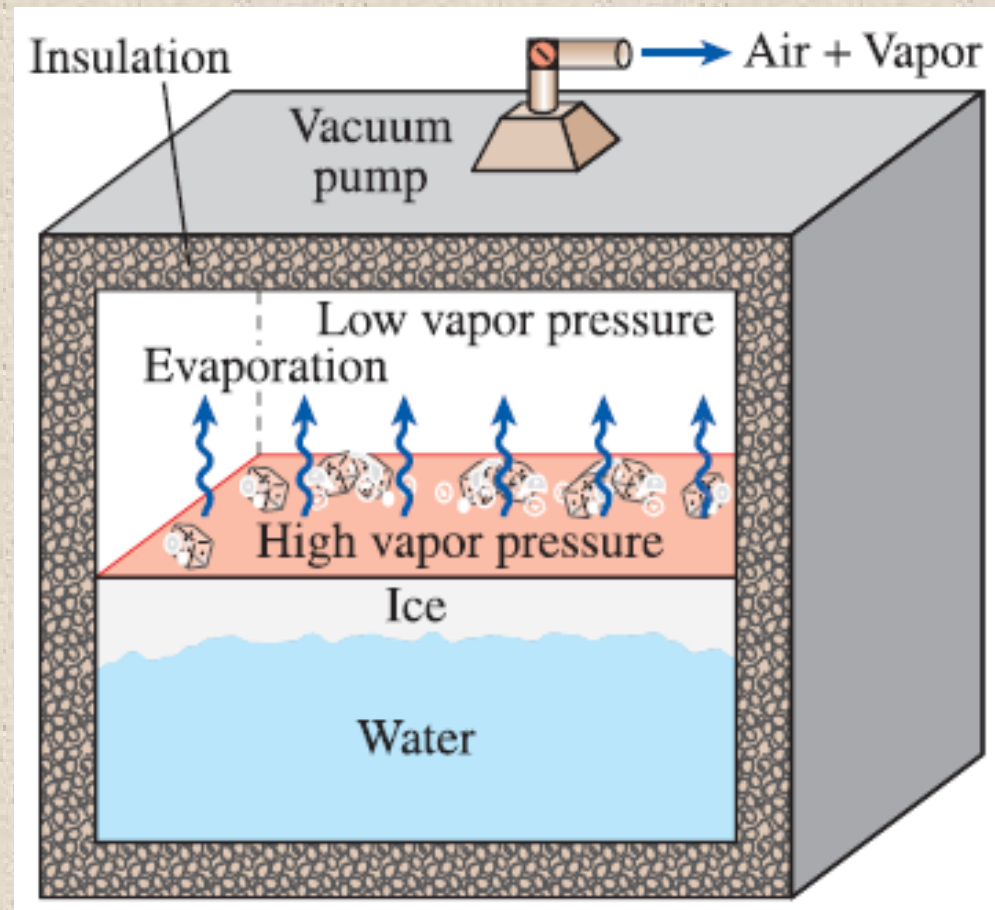
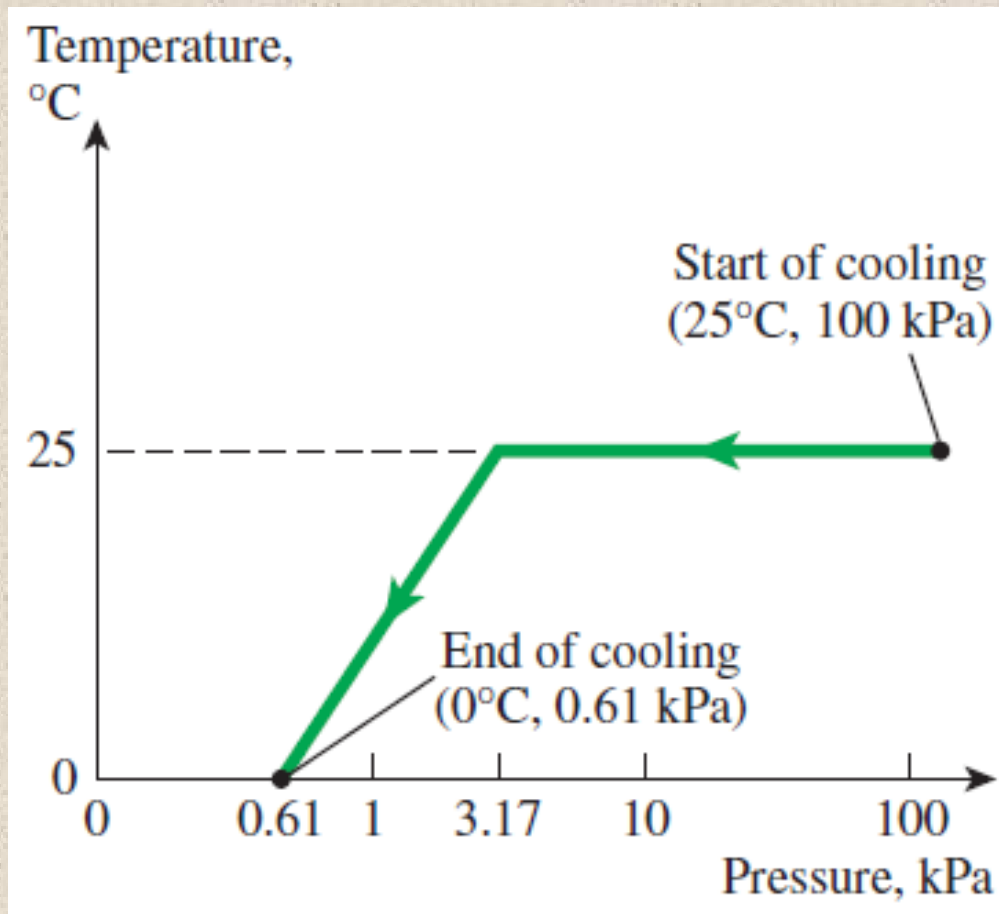


FIGURE 3-12

The temperature of liquid nitrogen exposed to the atmosphere remains constant at -196°C , and thus it maintains the test chamber at -196°C .

Some Consequences of T_{sat} and P_{sat} Dependence



The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C

In 1775, ice was made by evacuating the air space in a water tank

T-v diagram

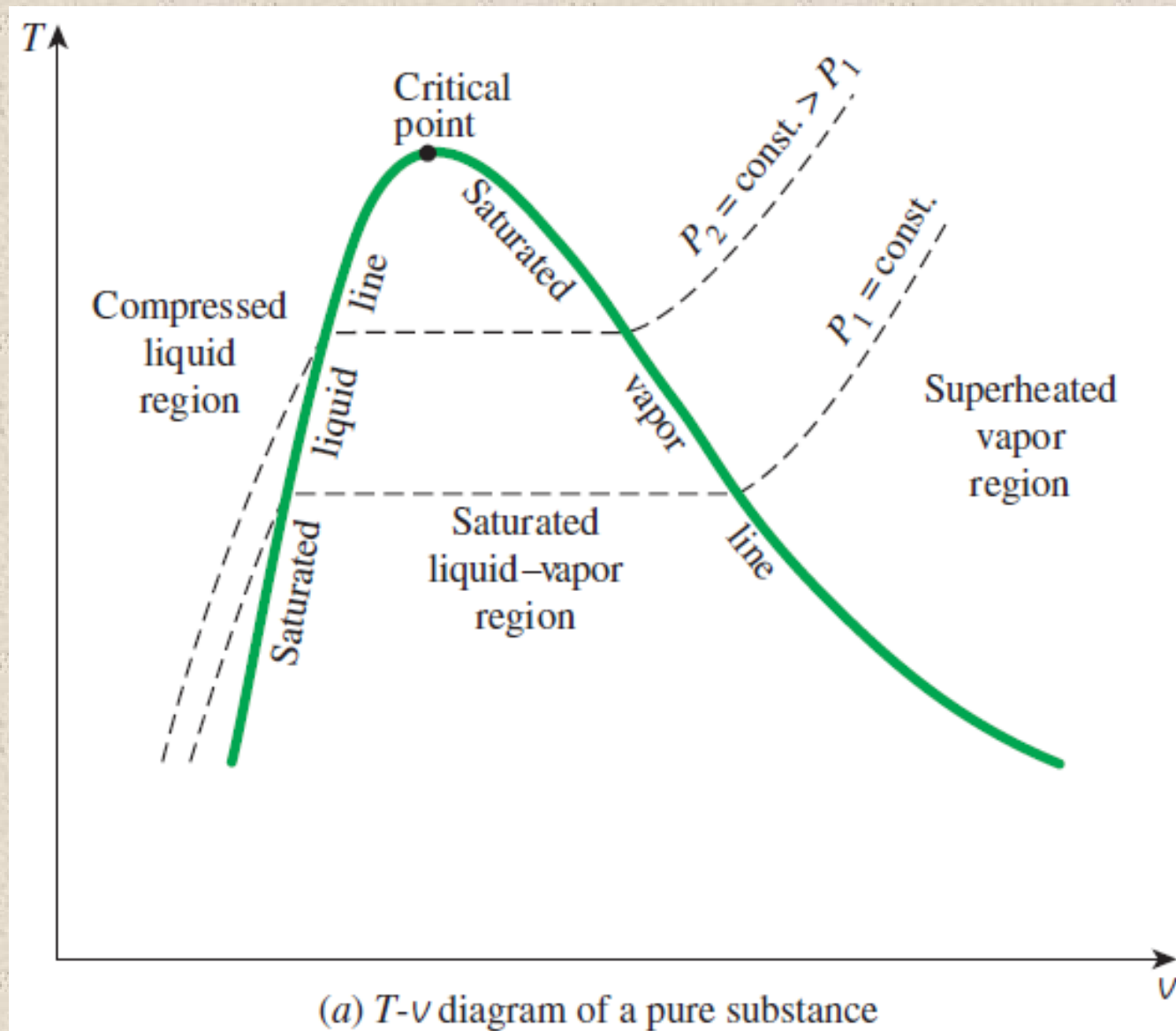


FIGURE 3-17

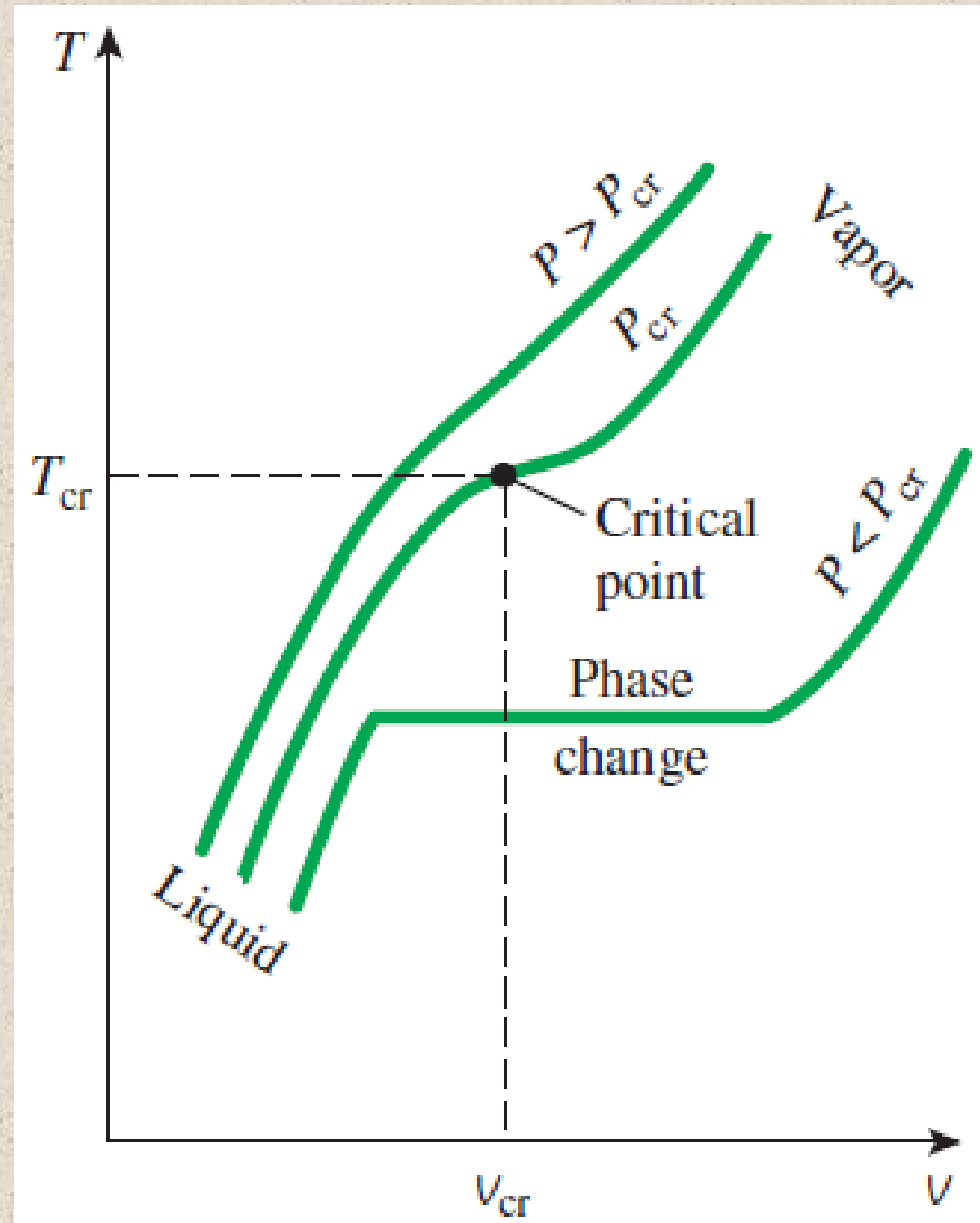
Property diagrams of a pure substance.

Critical point

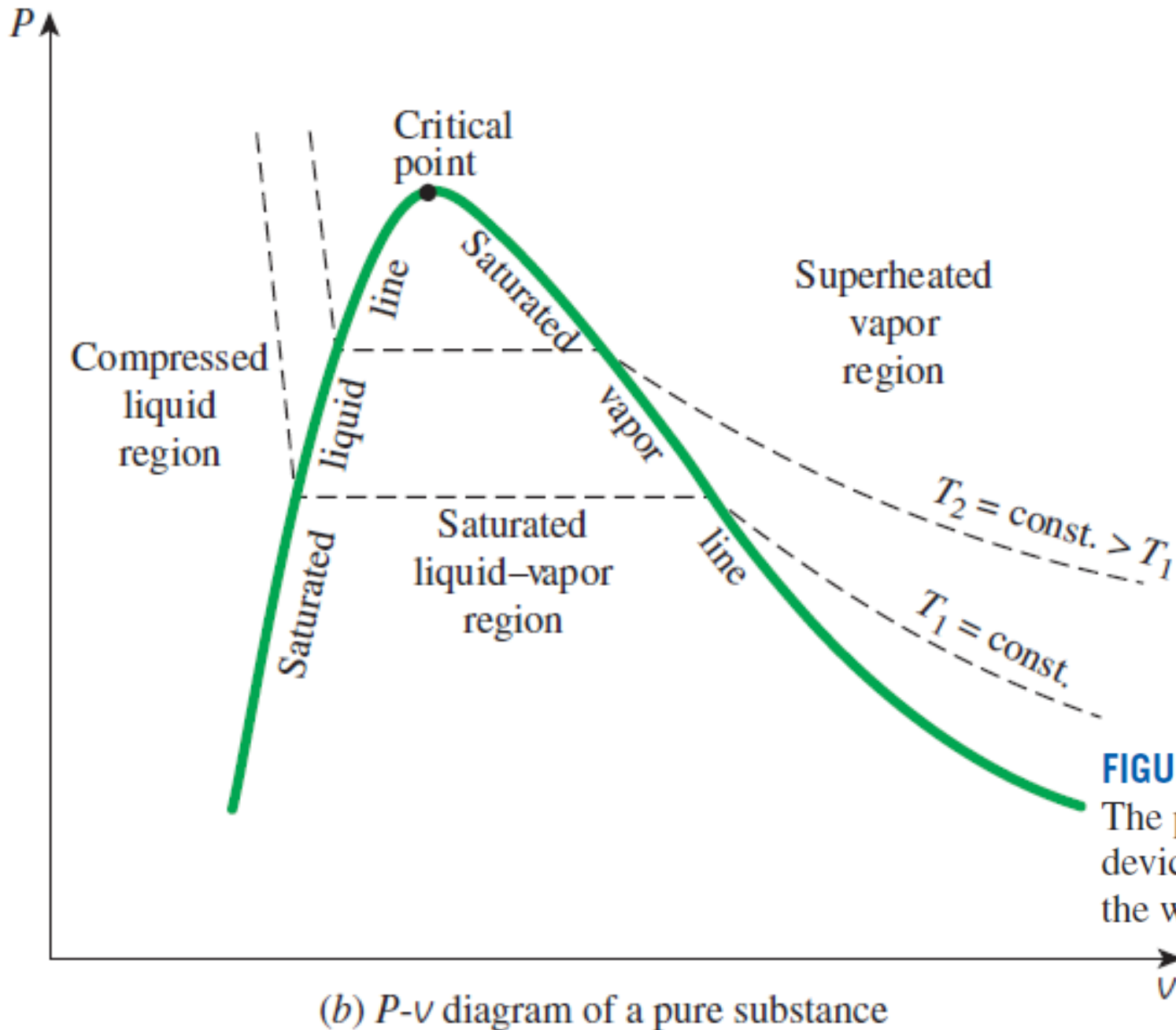
Critical point: The point at which the saturated liquid and saturated vapor states are identical

At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process

A **supercritical fluid (SCF)** is any substance at a temperature and pressure above its critical point



P-v diagram



Water is allowed to exchange heat with the surroundings so that its temperature remains constant

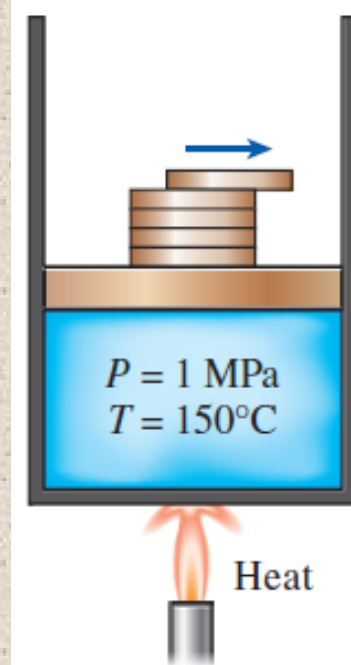
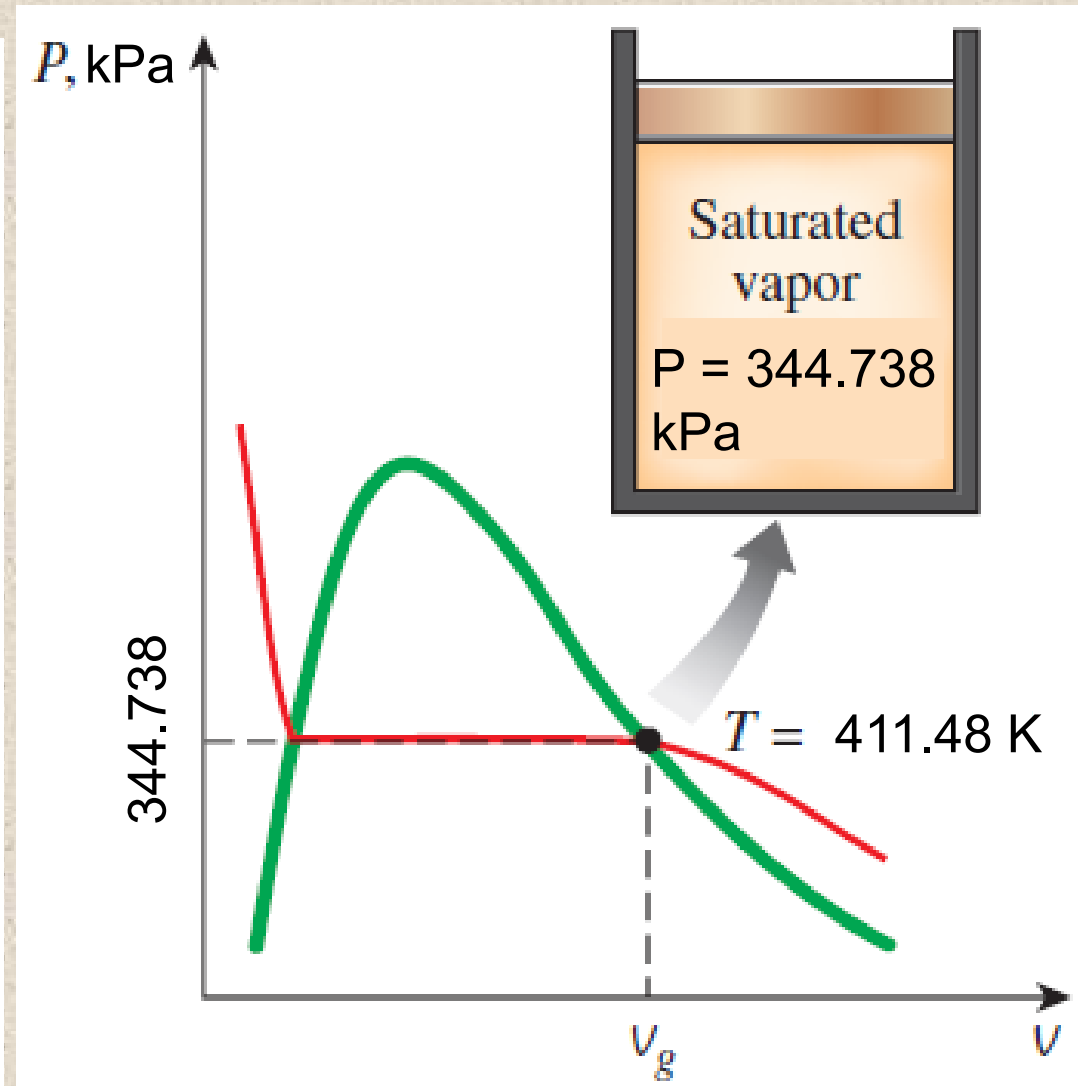
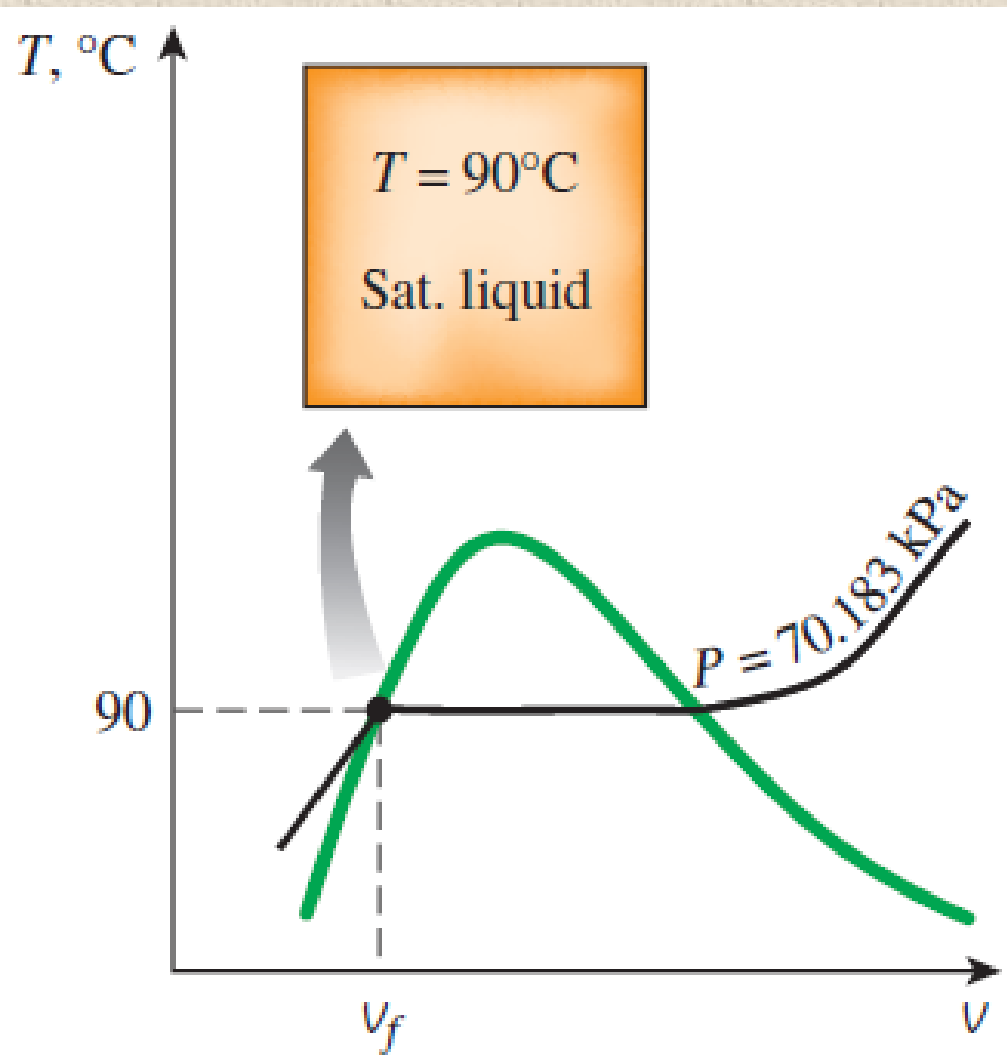


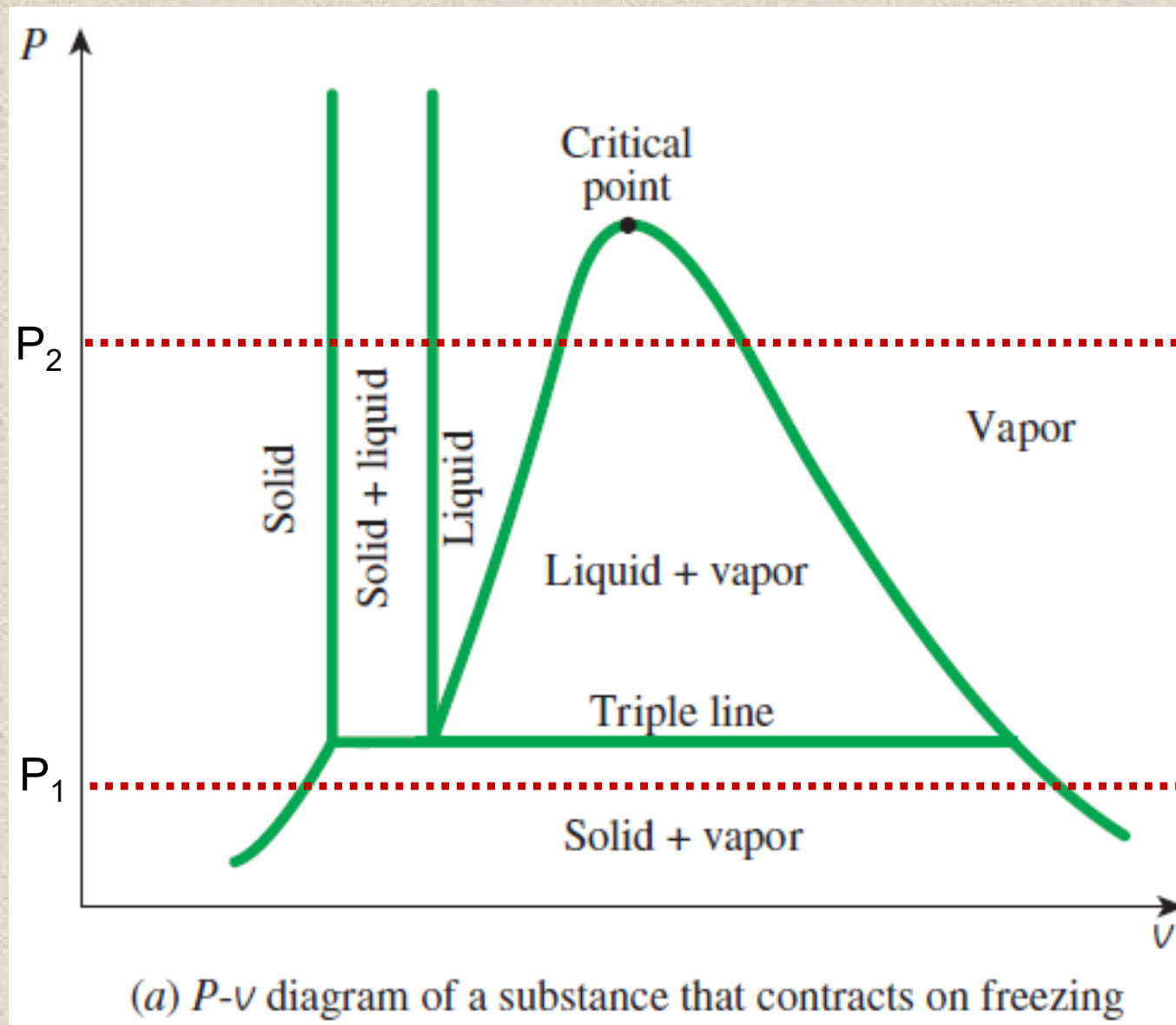
FIGURE 3-18

The pressure in a piston-cylinder device can be reduced by reducing the weight of the piston.

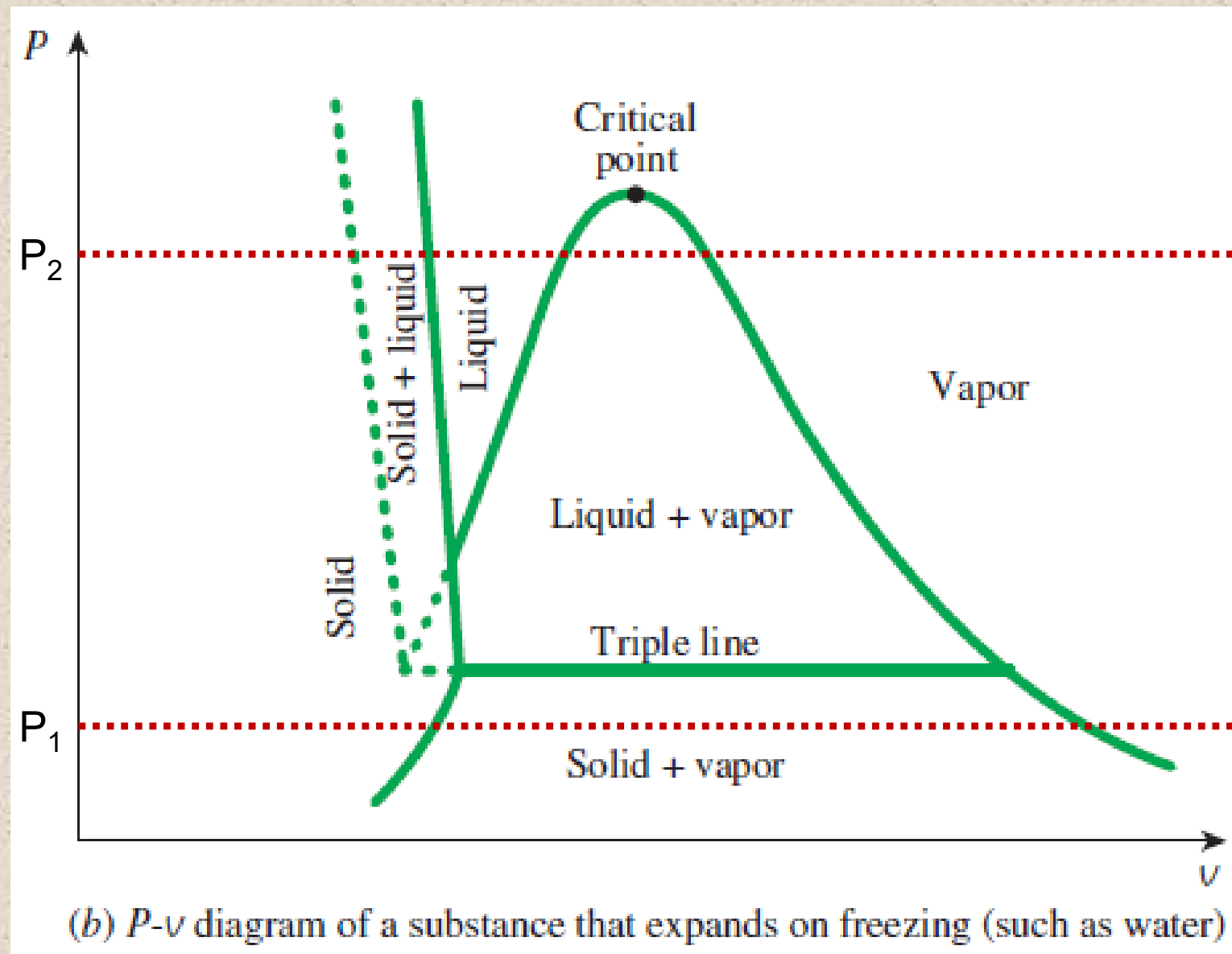
Saturated liquid and saturated vapor states of water on T - v and P - v diagrams



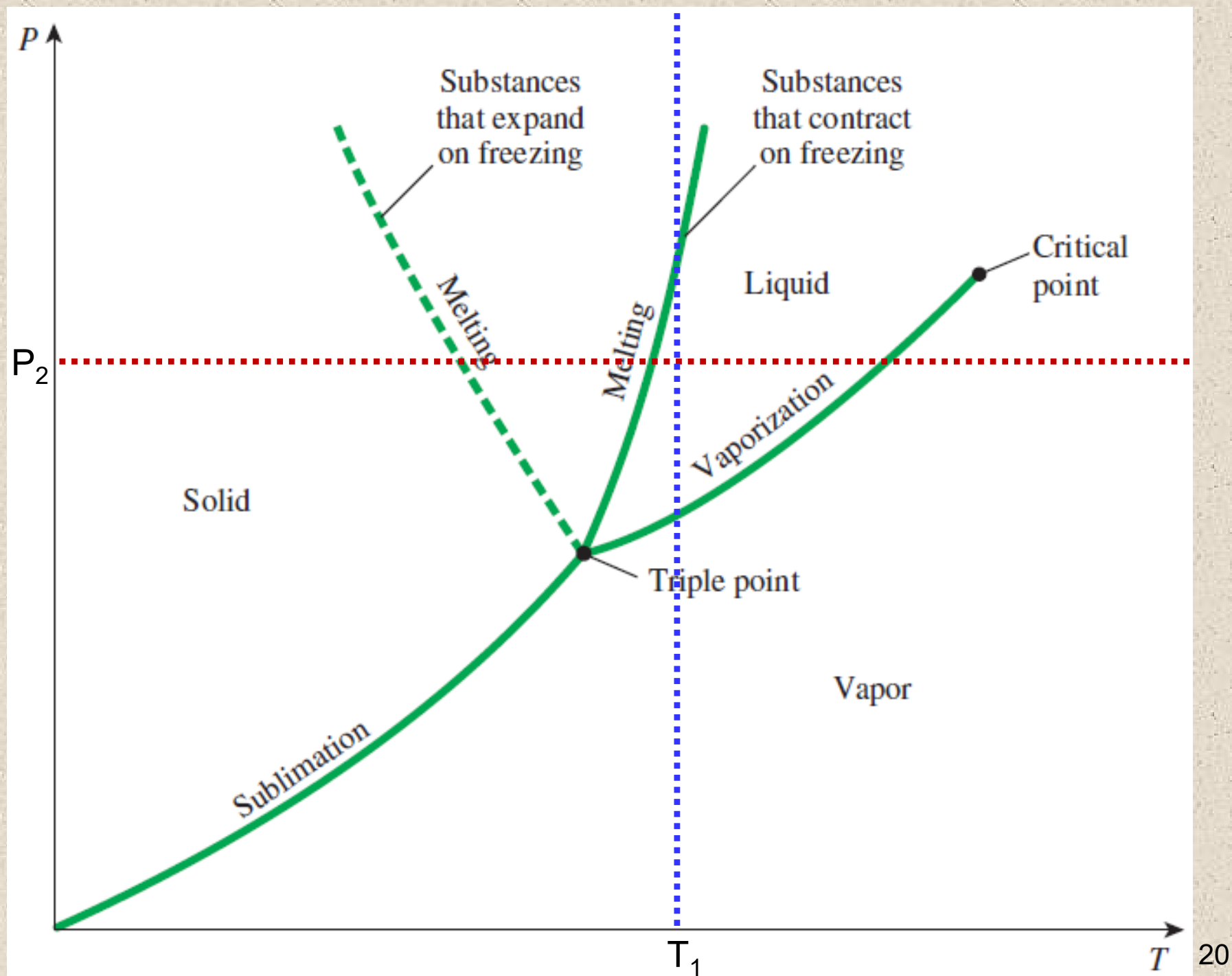
Extending the Diagrams to Include the Solid Phase for a Substance that Contracts on Cooling



Extending the Diagrams to Include the Solid Phase for a Substance that Expands on Freezing



Phase (P-T) Diagram of Pure Substances



Sublimation: Passing from the solid phase directly into the vapor phase



At low pressures (below the triple-point value), solids evaporate without melting first (*sublimation*)

Triple Point

- At triple-point pressure and temperature, a substance exists in three phases in equilibrium

For water,
 $T_{tp} = 0.01^{\circ}\text{C}$
 $P_{tp} = 0.6117 \text{ kPa}$



The P - v - T surfaces present a great deal of information at once, but in a thermodynamic analysis it is more convenient to work with two-dimensional diagrams, such as the P - v and T - v diagrams

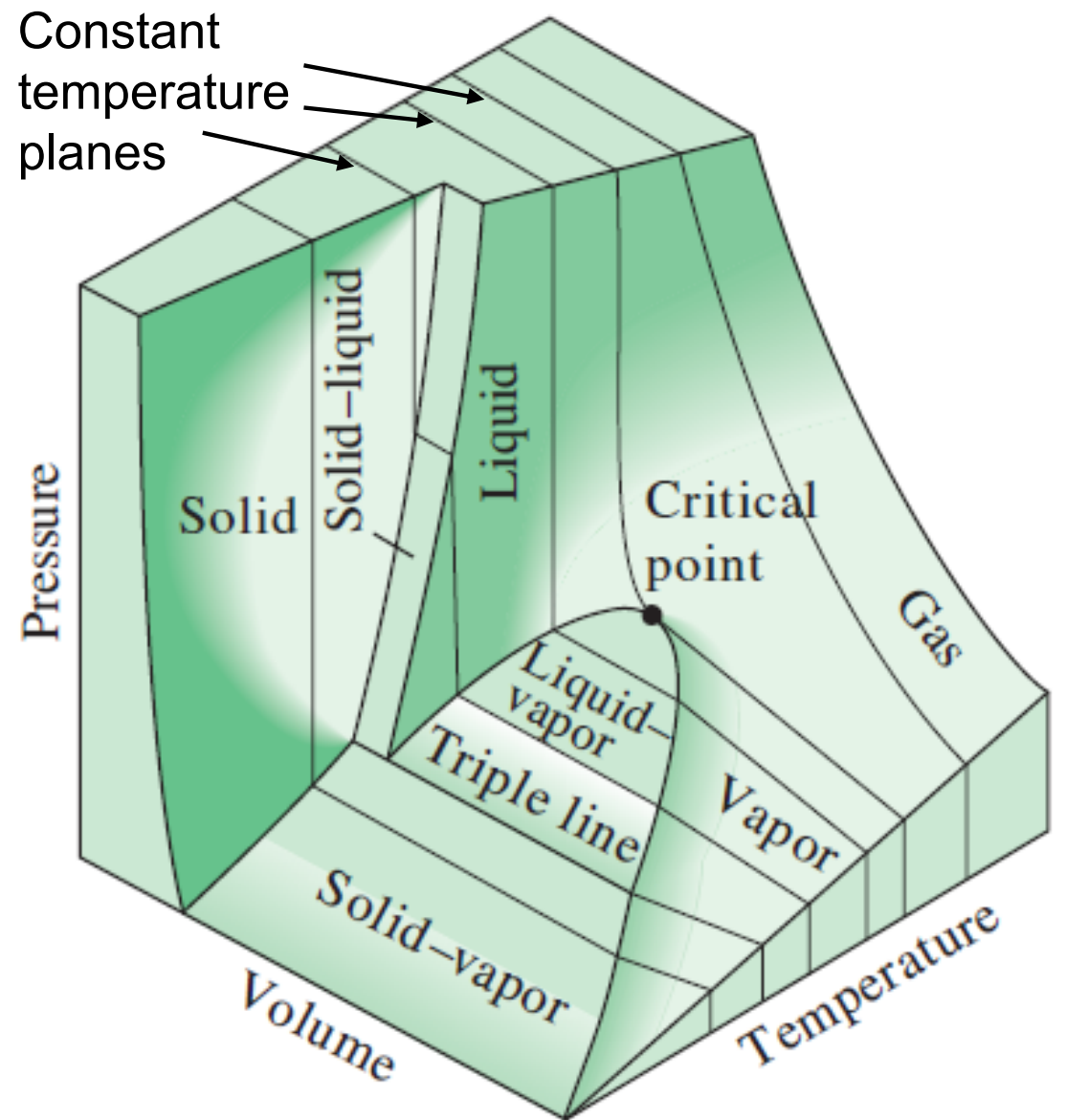


FIGURE 3-23
 P - v - T surface of a substance that contracts on freezing.

Try to visualize the Pv , PT and Tv diagrams (2D) from this 3D representation and see if they resemble the 2D representations

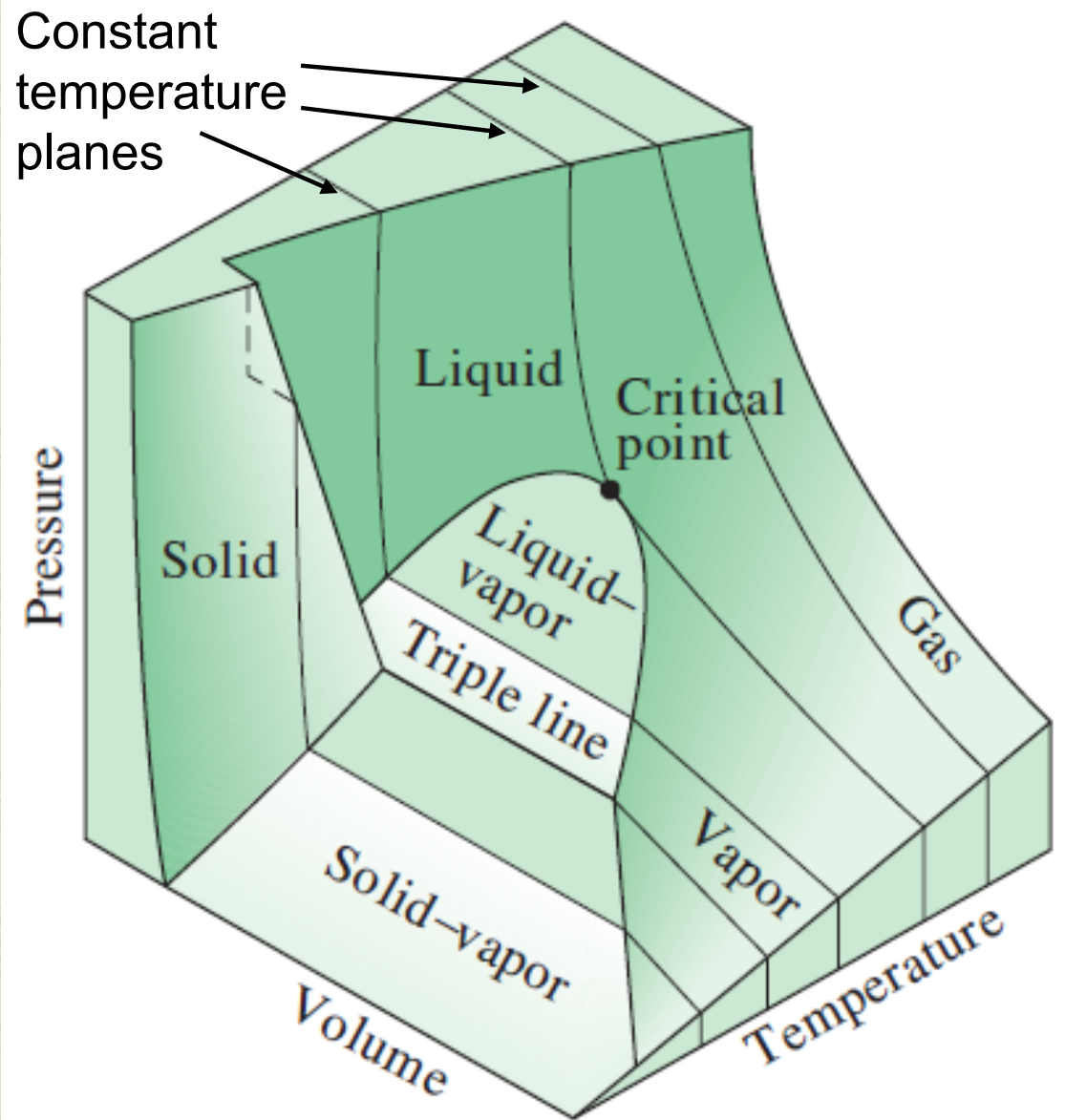


FIGURE 3-24

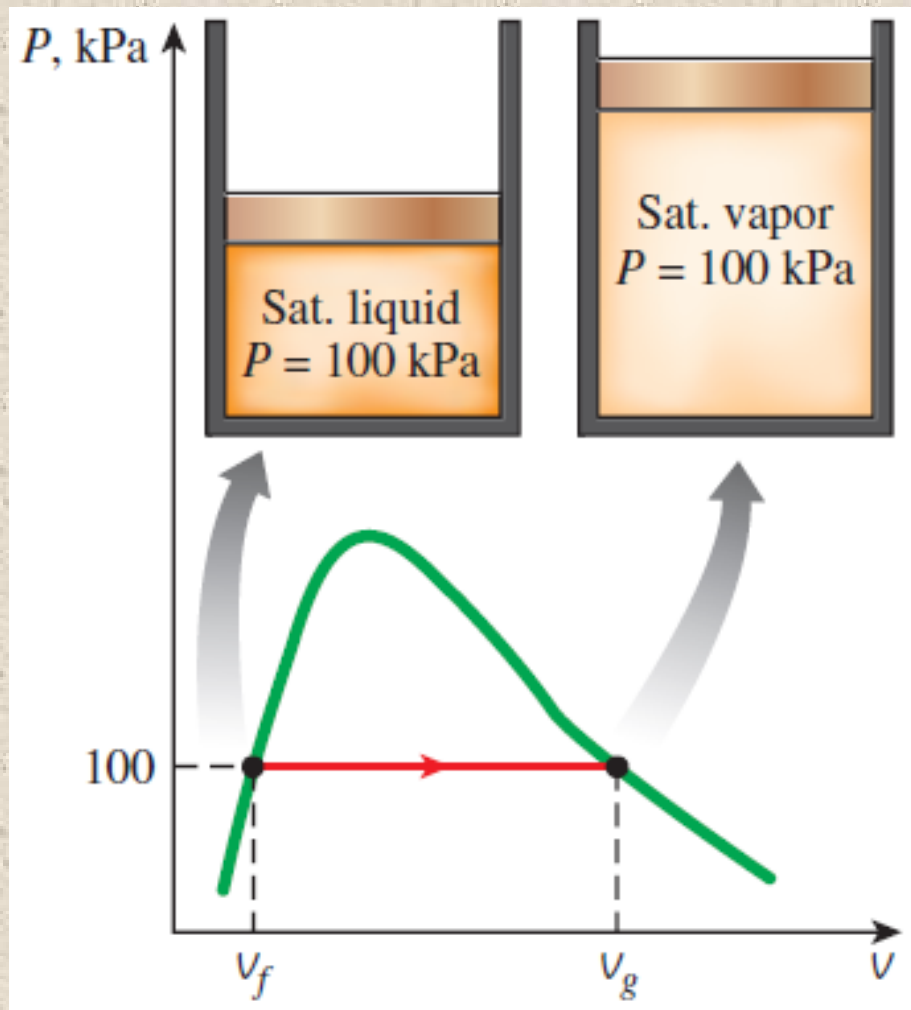
$P-v-T$ surface of a substance that *expands* on freezing (like water).

PROPERTY TABLES

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations
- Therefore, properties are frequently presented in the form of tables
- Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties
- The results of these measurements and calculations are presented in tables in a convenient format

Property Table

A partial list of Table A-4



Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg	
		Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

v_{fg} = difference between v_g and v_f (that is $v_{fg} = v_g - v_f$)

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			Entropy, kJ/kg·K		
		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

Saturated Liquid–Vapor Mixture

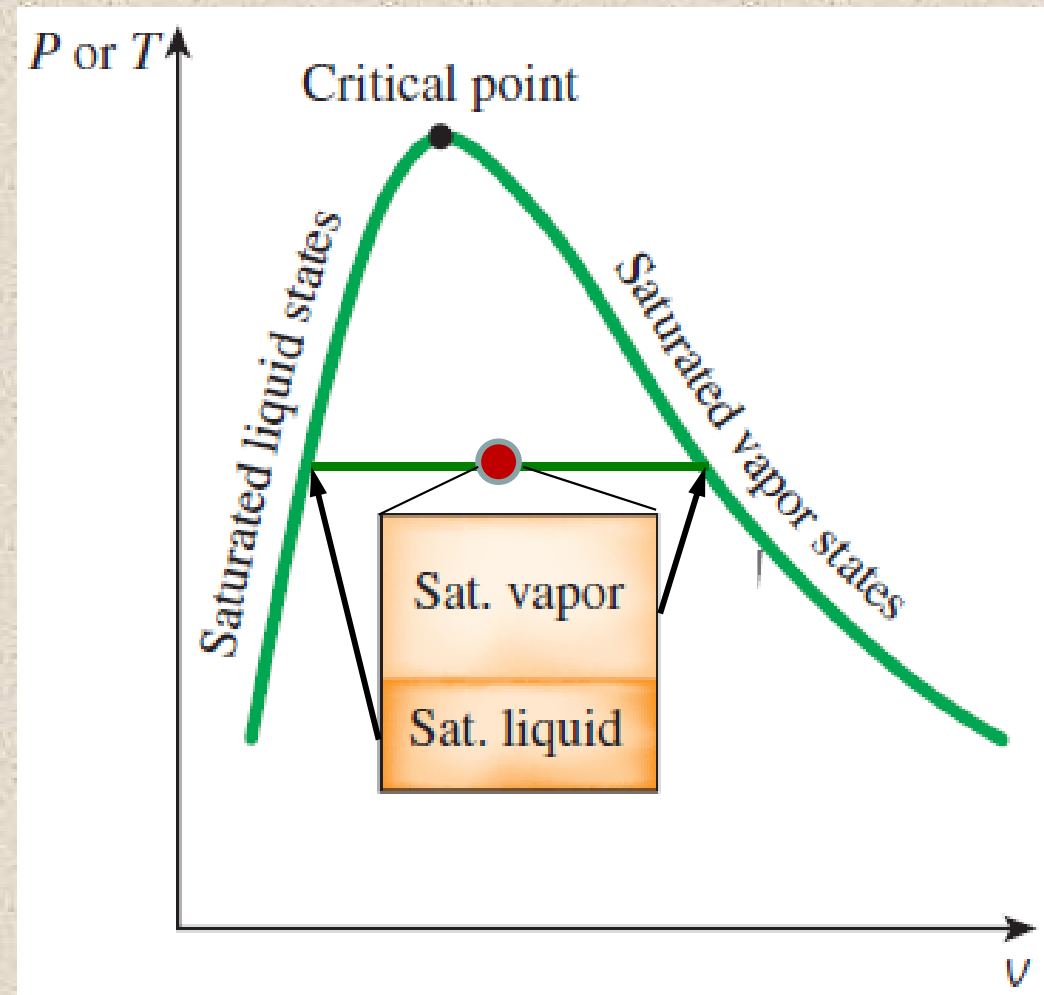
- The relative amounts of liquid and vapor phases in a saturated mixture are specified by the **quality x**
- **Quality, x** : The ratio of the **mass of vapor** to the total mass of the mixture.
- **Quality is between 0 (sat. liquid) and 1 (sat. vapor)**

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

$$m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}}$$

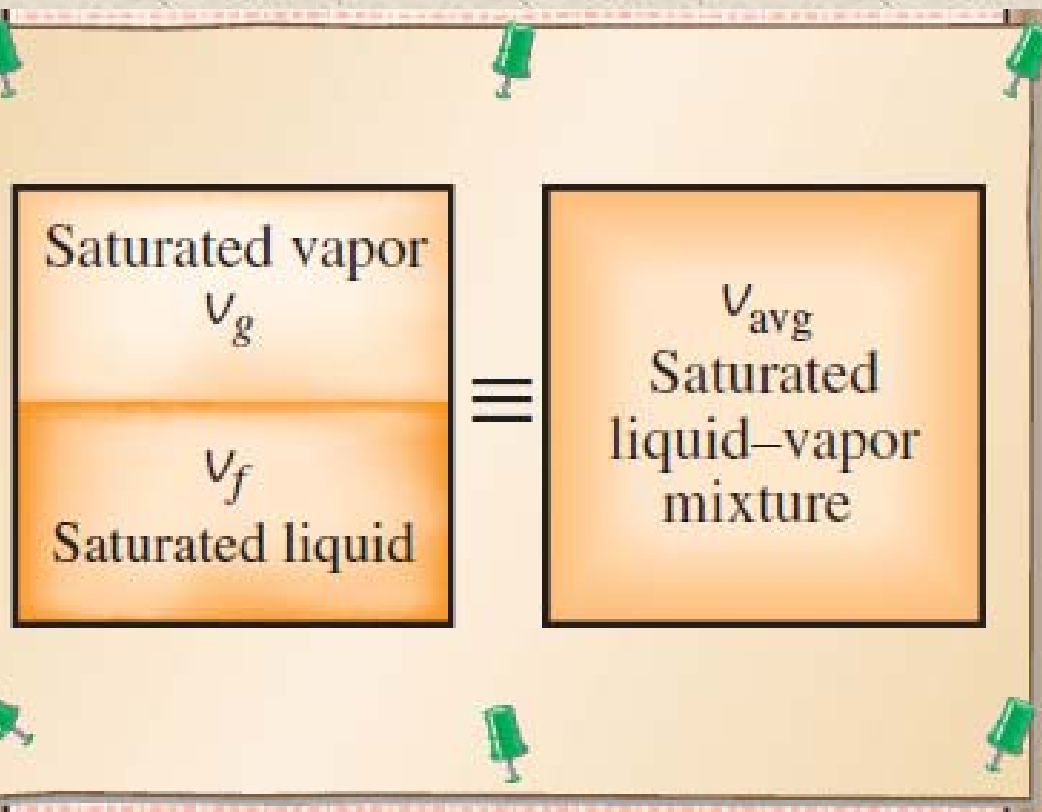
$$m_{\text{total}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture



Saturated Liquid–Vapor Mixture

- The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor*



A two-phase system can be treated as a homogeneous mixture for convenience

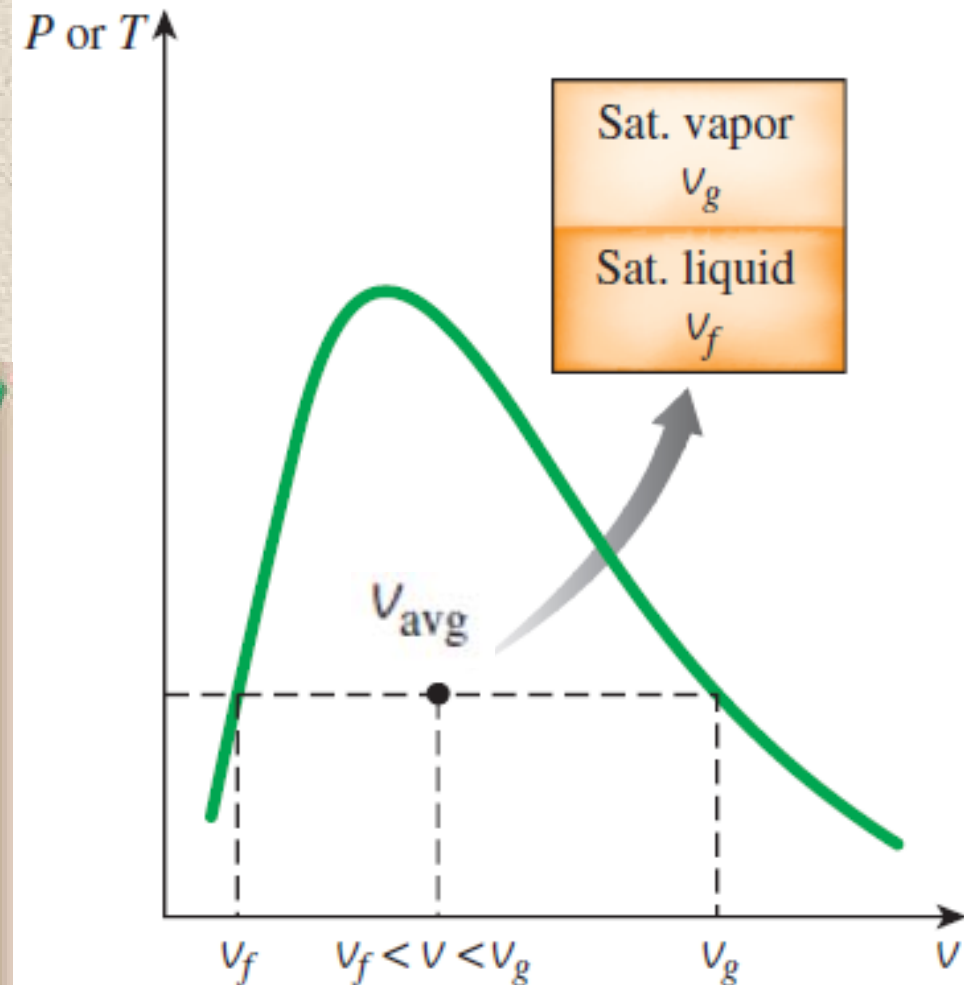


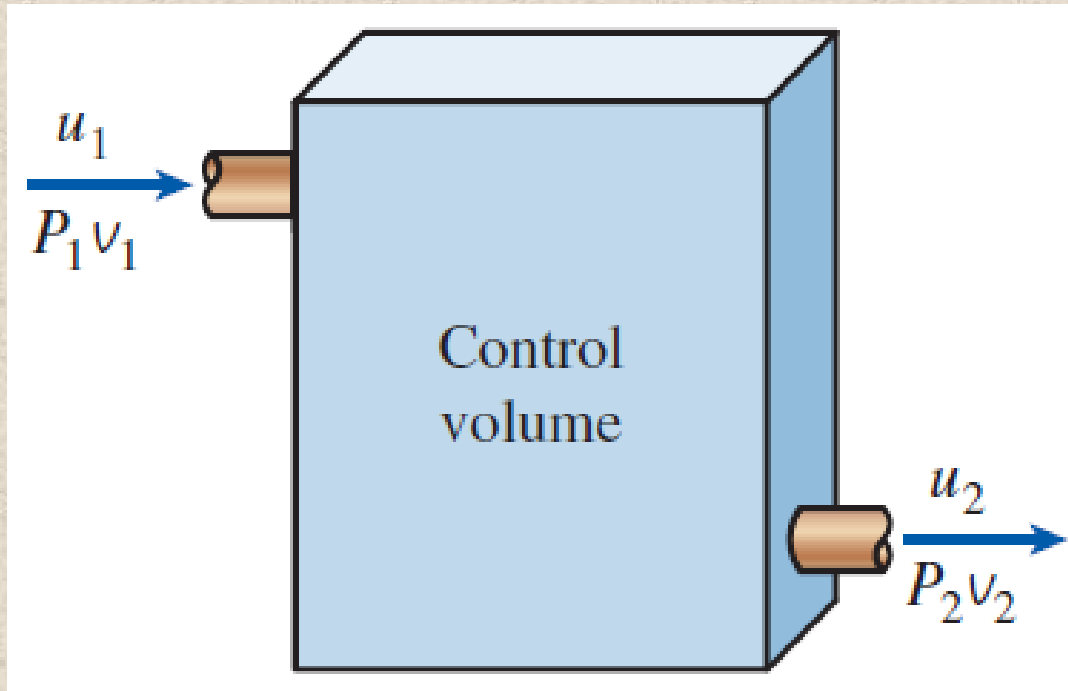
FIGURE 3–34

The ν value of a saturated liquid–vapor mixture lies between the ν_f and ν_g values at the specified T or P .

ENTHALPY

$$h = u + Pv \quad (\text{kJ/kg})$$

$$H = U + PV \quad (\text{kJ})$$



$$\begin{aligned} \text{kPa} \cdot \text{m}^3 &\equiv \text{kJ} \\ \text{kPa} \cdot \text{m}^3 / \text{kg} &\equiv \text{kJ/kg} \\ \text{bar} \cdot \text{m}^3 &\equiv 100 \text{ kJ} \\ \text{MPa} \cdot \text{m}^3 &\equiv 1000 \text{ kJ} \\ \text{psi} \cdot \text{ft}^3 &\equiv 0.18505 \text{ Btu} \end{aligned}$$

The product *pressure* \times *volume* has energy units

The combination $u + Pv$ is frequently encountered in the analysis of control volumes

- **Latent heat:** The amount of energy absorbed or released during a phase-change process
- **Latent heat of fusion:** The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization (h_{fg}):** The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation
- The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs
- At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg
- At 2 bar pressure the latent heat of vaporization of water is 2201.6 kJ/kg

Property of Saturated Liquid–Vapor Mixture

$$V = V_f + V_g$$

$$V = mV \longrightarrow m_t V_{\text{avg}} = m_f V_f + m_g V_g$$

$$m_f = m_t - m_g \longrightarrow m_t V_{\text{avg}} = (m_t - m_g) V_f + m_g V_g$$

Dividing by m_t yields

$$V_{\text{avg}} = (1 - x) V_f + x V_g$$

$$x = m_g / m_t.$$

$$V_{\text{avg}} = V_f + x V_{fg} \quad (\text{m}^3/\text{kg})$$

$$x = \frac{V_{\text{avg}} - V_f}{V_{fg}}$$

Property of Saturated Liquid–Vapor Mixture

$$x = m_g / m_t$$

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

$$v_{\text{avg}} = v_f + x v_{fg} \quad (\text{m}^3/\text{kg})$$

$$u_{\text{avg}} = u_f + x u_{fg} \quad (\text{kJ}/\text{kg})$$

$$h_{\text{avg}} = h_f + x h_{fg} \quad (\text{kJ}/\text{kg})$$

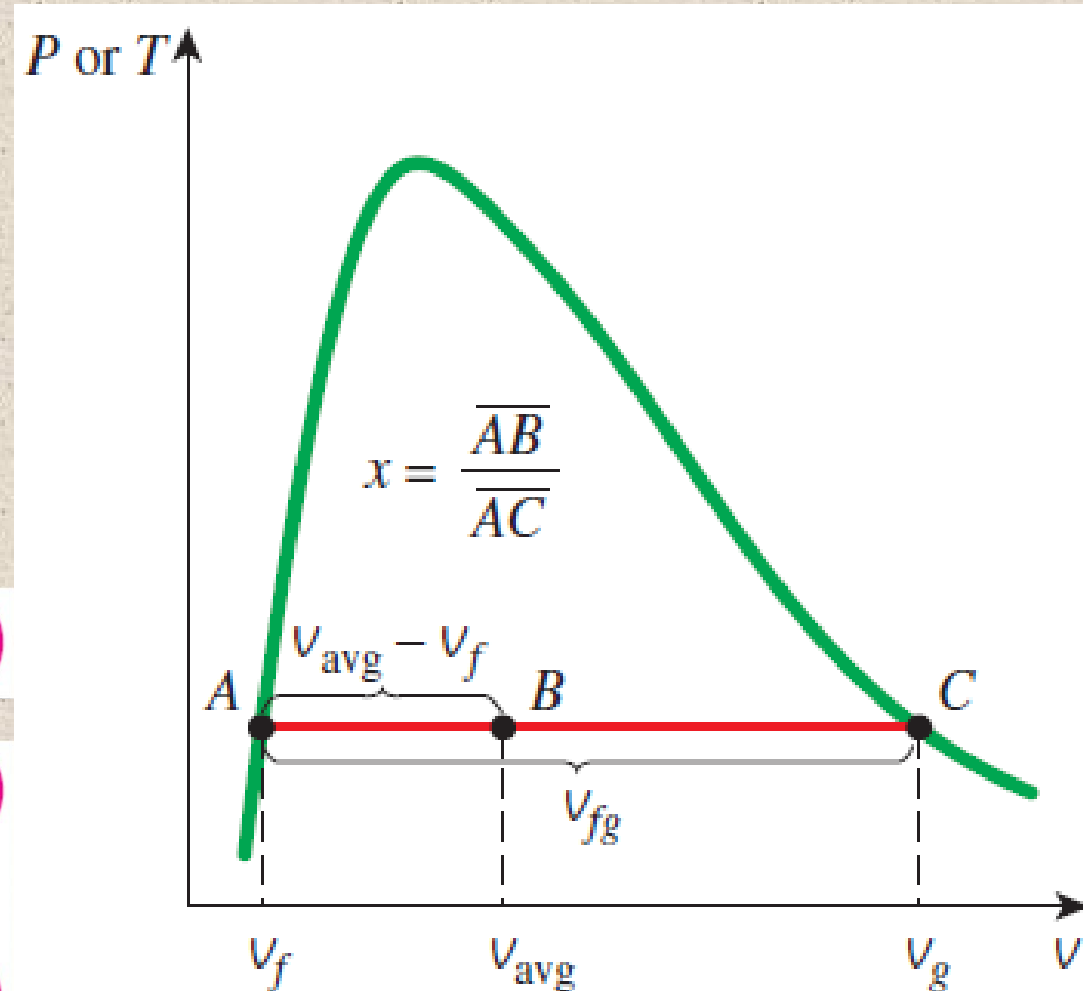


FIGURE 3–33

Quality is related to the horizontal distances on P - v and T - v diagrams.

Example: Saturated liquid-vapor mixture states

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 (b) the volume of the tank

At $T = 90\text{ °C}$, $P_{\text{sat}} = 70.183\text{ kPa}$

$$m_t = m_g + m_f = 10\text{ kg}$$

$$x = m_g/m_t = 0.2$$

$$v_{fg} = v_g - v_f = 2.3583\text{ m}^3/\text{kg}$$

$$v_{\text{avg}} = v_f + xv_{fg} = 0.4727\text{ m}^3/\text{kg}$$

$$V = m_t v_{\text{avg}} = 4.73\text{ m}^3$$

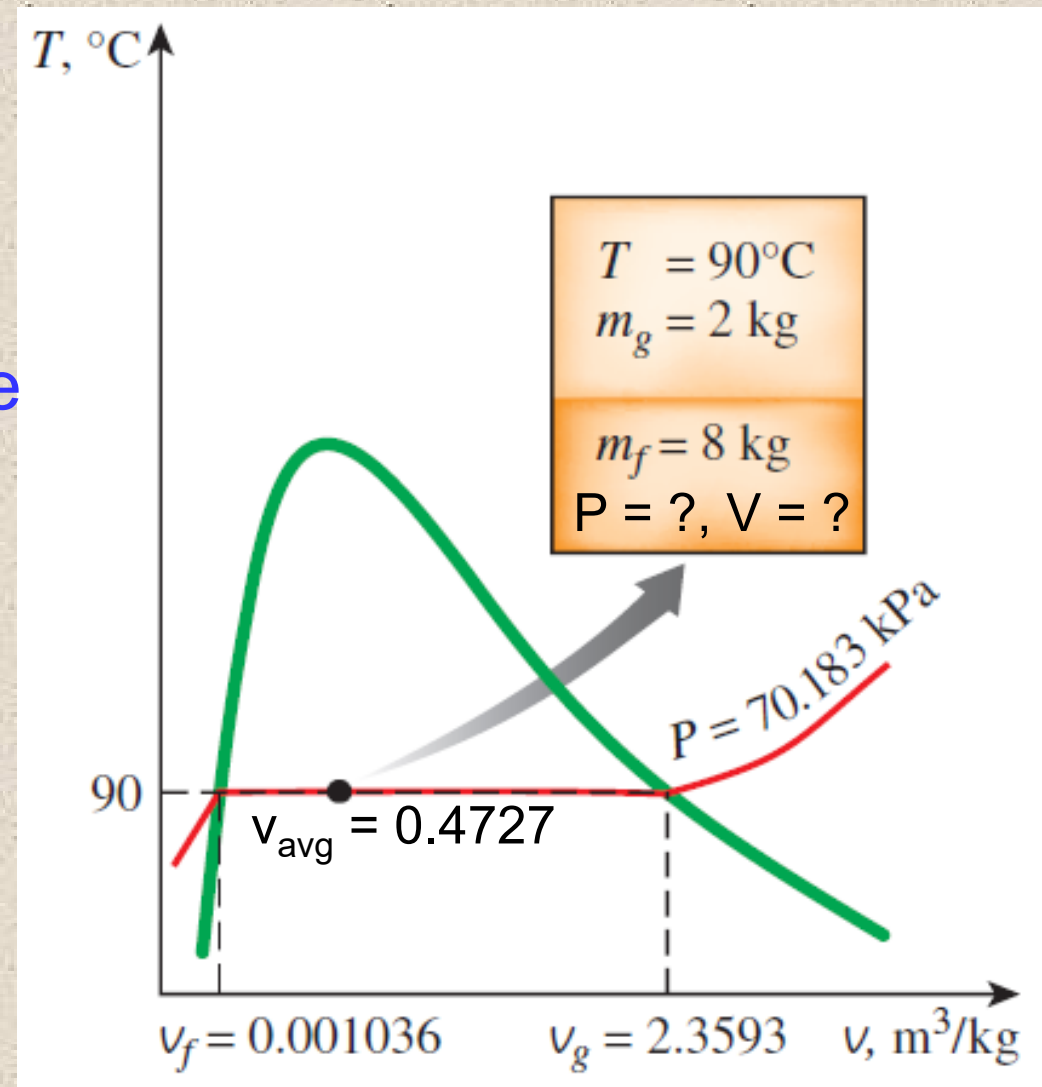


TABLE A-4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		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
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292

Example: Saturated liquid-vapor mixture

An 80 L vessel contains 4 kg of **refrigerant-134a** at a pressure of 160 kPa.

Determine (a) temperature, (b) the quality, (c) the enthalpy of the refrigerant

At $P = 160 \text{ kPa}$, $T_{\text{sat}} = -15.60^\circ\text{C}$

$$v_{\text{avg}} = V/m = 0.02 \text{ m}^3/\text{kg}$$

$$v_{\text{fg}} = v_g - v_f = 0.1228 \text{ m}^3/\text{kg}$$

$$h_{\text{fg}} = h_g - h_f = 209.96 \text{ kJ/kg}$$

$$x = (v_{\text{avg}} - v_f)/v_{\text{fg}} = 0.157$$

$$h_{\text{avg}} = h_f + xh_{\text{fg}} = 64.2 \text{ kJ/kg}$$

$$H = m_t h_{\text{avg}} = 256.8 \text{ kJ}$$

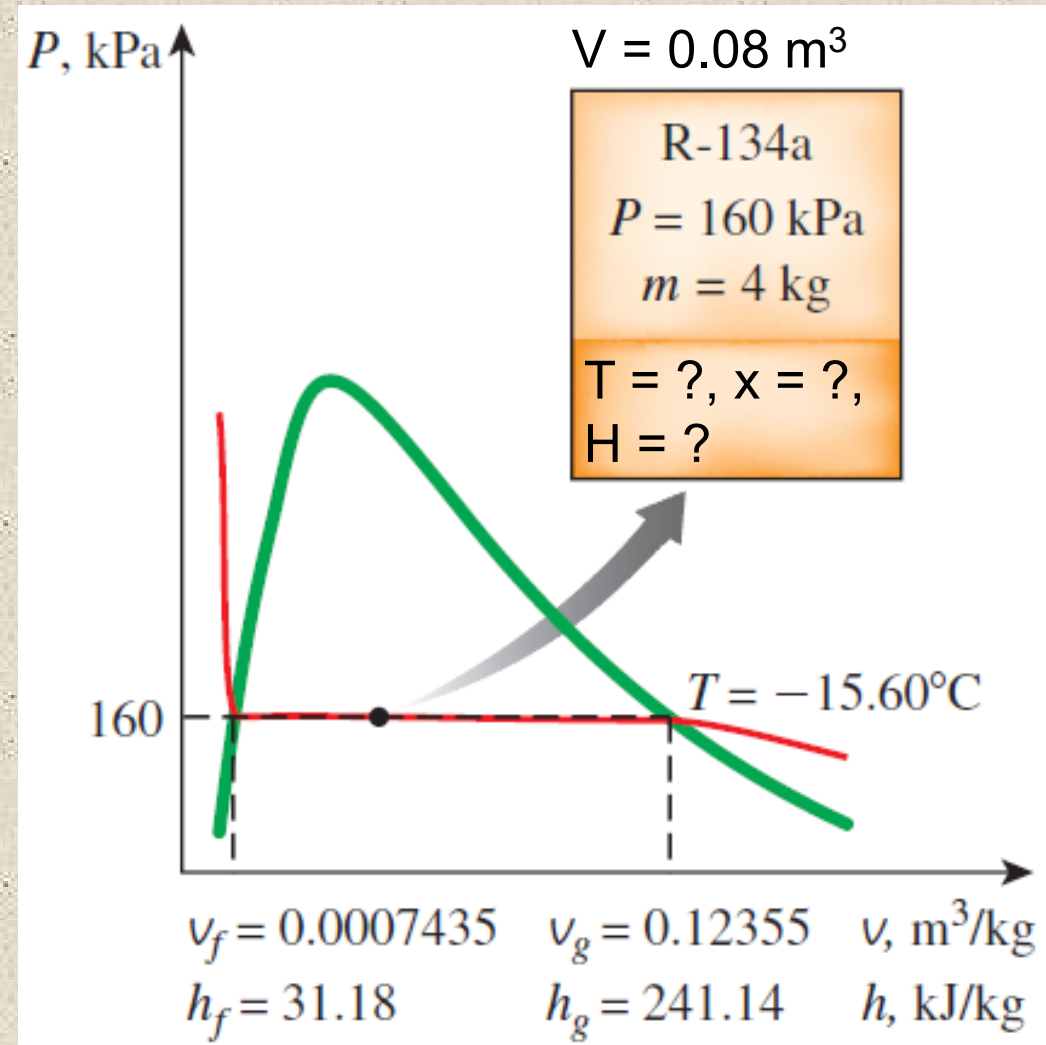


TABLE A-12

Saturated refrigerant-134a—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		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
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467
160	−15.60	0.0007435	0.12355	31.06	190.31	221.37	31.18	209.96	241.14	0.12686	0.81517	0.94202
180	−12.73	0.0007485	0.11049	34.81	188.20	223.01	34.94	207.95	242.90	0.14131	0.79848	0.93979
200	−10.09	0.0007532	0.099951	38.26	186.25	224.51	38.41	206.09	244.50	0.15449	0.78339	0.93788
240	−5.38	0.0007618	0.083983	44.46	182.71	227.17	44.64	202.68	247.32	0.17786	0.75689	0.93475
280	−1.25	0.0007697	0.072434	49.95	179.54	229.49	50.16	199.61	249.77	0.19822	0.73406	0.93228
320	2.46	0.0007771	0.063681	54.90	176.65	231.55	55.14	196.78	251.93	0.21631	0.71395	0.93026
360	5.82	0.0007840	0.056809	59.42	173.99	233.41	59.70	194.15	253.86	0.23265	0.69591	0.92856
400	8.91	0.0007905	0.051266	63.61	171.49	235.10	63.92	191.68	255.61	0.24757	0.67954	0.92711
450	12.46	0.0007983	0.045677	68.44	168.58	237.03	68.80	188.78	257.58	0.26462	0.66093	0.92555
500	15.71	0.0008058	0.041168	72.92	165.86	238.77	73.32	186.04	259.36	0.28021	0.64399	0.92420
550	18.73	0.0008129	0.037452	77.09	163.29	240.38	77.54	183.44	260.98	0.29460	0.62842	0.92302
600	21.55	0.0008198	0.034335	81.01	160.84	241.86	81.50	180.95	262.46	0.30799	0.61398	0.92196
650	24.20	0.0008265	0.031680	84.72	158.51	243.23	85.26	178.56	263.82	0.32052	0.60048	0.92100
700	26.69	0.0008331	0.029392	88.24	156.27	244.51	88.82	176.26	265.08	0.33232	0.58780	0.92012
750	29.06	0.0008395	0.027398	91.59	154.11	245.70	92.22	174.03	266.25	0.34348	0.57582	0.91930
800	31.31	0.0008457	0.025645	94.80	152.02	246.82	95.48	171.86	267.34	0.35408	0.56445	0.91853
850	33.45	0.0008519	0.024091	97.88	150.00	247.88	98.61	169.75	268.36	0.36417	0.55362	0.91779
900	35.51	0.0008580	0.022703	100.84	148.03	248.88	101.62	167.69	269.31	0.37383	0.54326	0.91709
950	37.48	0.0008640	0.021456	103.70	146.11	249.82	104.52	165.68	270.20	0.38307	0.53333	0.91641
1000	39.37	0.0008700	0.020329	106.47	144.24	250.71	107.34	163.70	271.04	0.39196	0.52378	0.91574
1200	46.29	0.0008935	0.016728	116.72	137.12	253.84	117.79	156.12	273.92	0.42449	0.48870	0.91320
1400	52.40	0.0009167	0.014119	125.96	130.44	256.40	127.25	148.92	276.17	0.45325	0.45742	0.91067

Superheated Vapor

- In the region to the right of the saturated vapor line a substance exists as superheated vapor
- It is customary to refer to the substance as superheated vapor at temperatures above the critical temperature
- In this region, temperature and pressure are independent properties (single-phase only)

Compared to saturated vapor, superheated vapor is characterized by:

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

Higher temperatures ($T > T_{\text{sat}}$ 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)

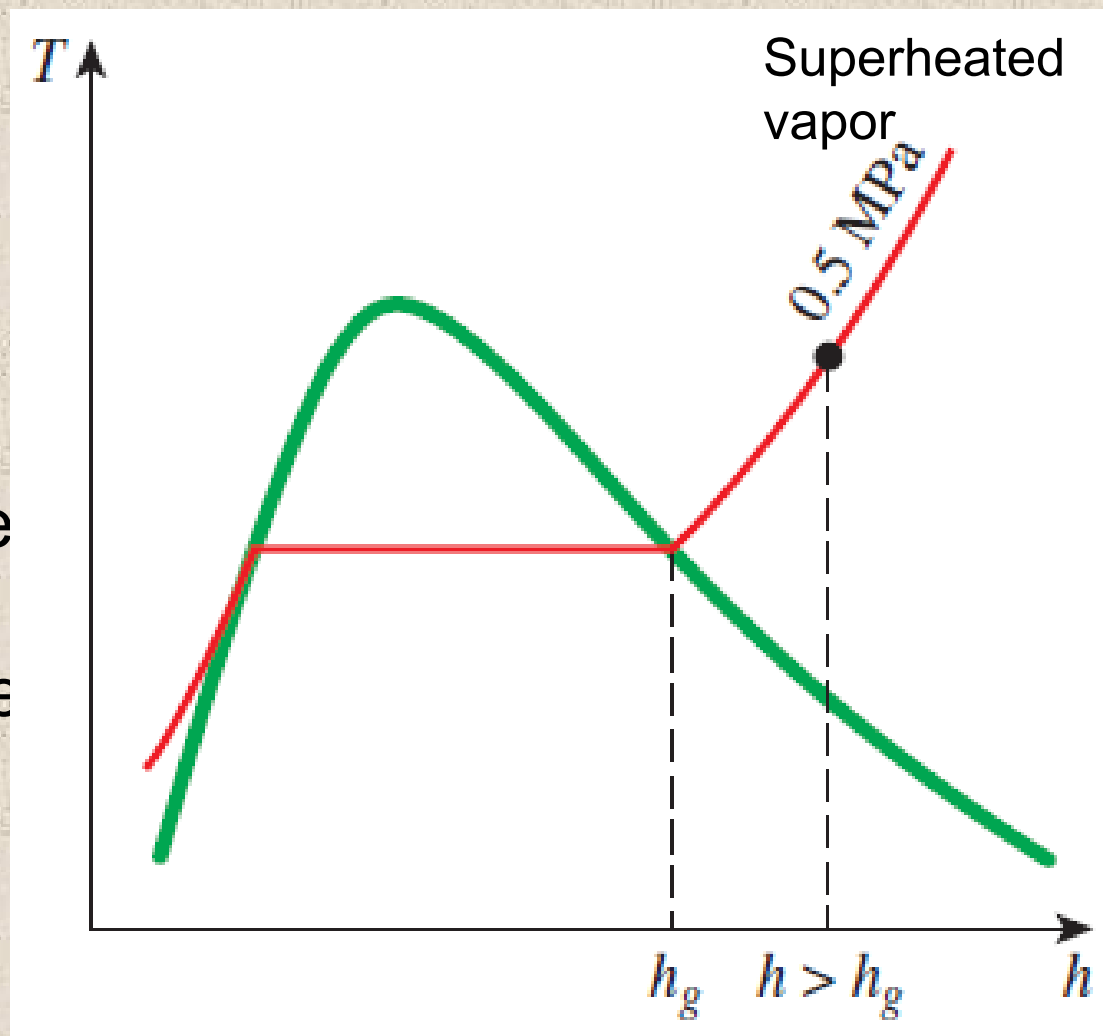


TABLE A-6

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	u kJ/kg	h kJ/kg	s kJ/kg·K
$P = 0.01 \text{ MPa (45.81°C)}^*$					$P = 0.05 \text{ MPa (81.32°C)}$				$P = 0.10 \text{ MPa (99.61°C)}$			
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
$P = 0.20 \text{ MPa (120.21°C)}$					$P = 0.30 \text{ MPa (133.52°C)}$				$P = 0.40 \text{ MPa (143.61°C)}$			
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

Compressed Liquid

- In the region to the left of the saturated liquid line a substance exists as compressed liquid
- It is customary to refer to the substance as compressed liquid at temperatures below the critical temperature

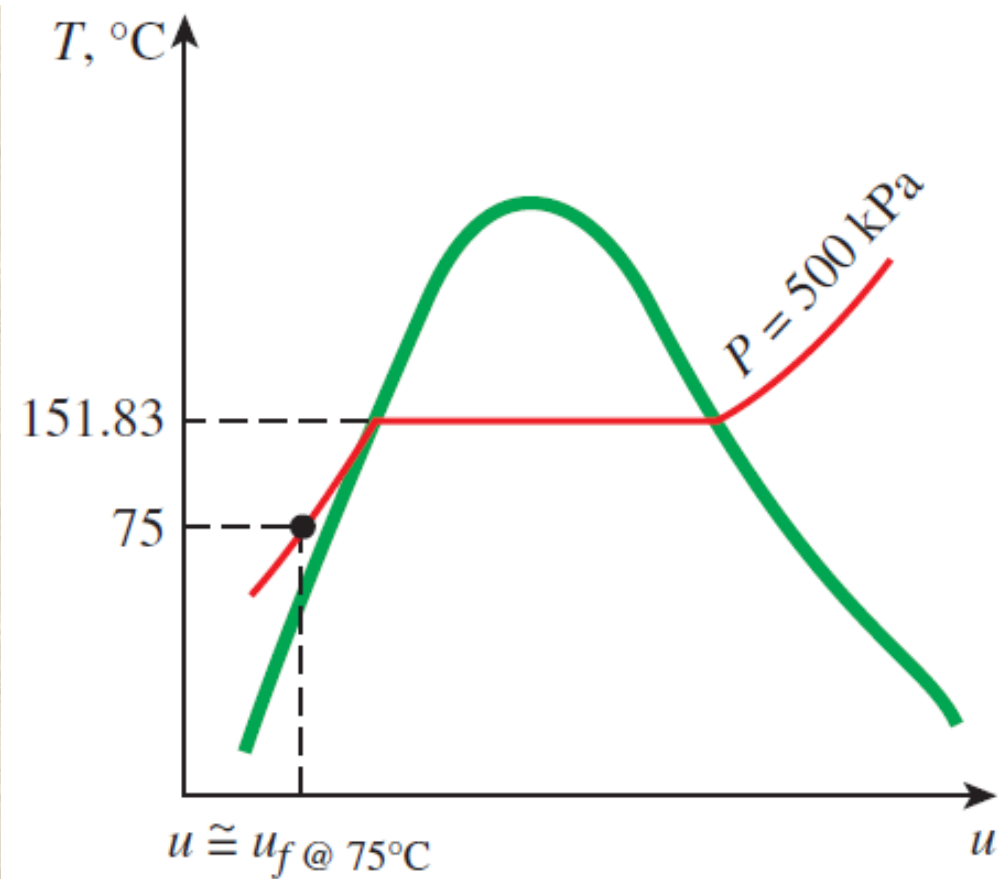


FIGURE 3–41

At a given P and T , a pure substance will exist as a compressed liquid if $T < T_{\text{sat}} @ P$.

Compressed liquid is characterized by

- Higher pressures ($P > P_{\text{sat}}$ at a given T)
- Lower temperatures ($T < T_{\text{sat}}$ 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)

Compressed Liquid Properties

Compressed liquid tables are not as commonly available.

One reason for this is the relative independence of compressed liquid properties from pressure

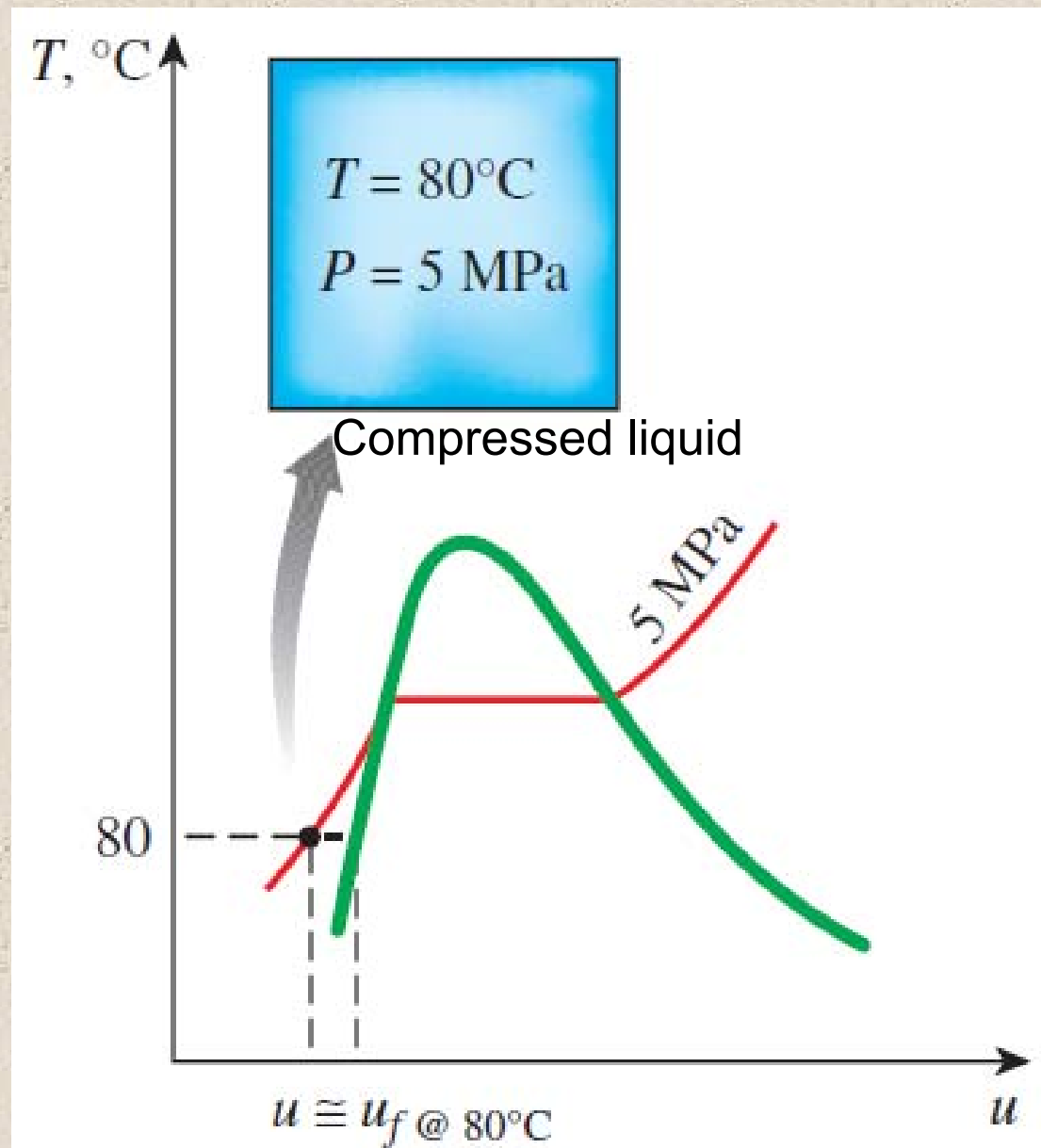
A compressed liquid may be approximated as a saturated liquid at the given temperature

Given: P and T

$$v \approx v_f @ T$$

$$u \approx u_f @ T$$

$$h \approx h_f @ T$$



Enthalpy of Compressed Liquid

Out of v (specific volume), u (internal energy) and h (enthalpy), the property whose value is most sensitive to variations in the pressure is the enthalpy h

Although the approximation results in negligible error in v and u , the error in h may reach undesirable levels

However, the error in h at low to moderate pressures and temperatures can be reduced significantly by evaluating it from instead of just taking it to be $h_{f@T}$

$$h = u + Pv$$

Approximate: $u \cong u_{f@T}$ $v \cong v_{f@T}$

$$h \cong u_{f@T} + Pv_{f@T}$$

$$u_{f@T} = h_{f@T} - P_{sat@T}v_{f@T}$$

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

TABLE A-7

Compressed liquid 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	u kJ/kg	h kJ/kg	s kJ/kg·K
$P = 5 \text{ MPa (263.94°C)}$					$P = 10 \text{ MPa (311.00°C)}$				$P = 15 \text{ MPa (342.16°C)}$			
Sat.	0.0012862	1148.1	1154.5	2.9207	0.0014522	1393.3	1407.9	3.3603	0.0016572	1585.5	1610.3	3.6848
0	0.0009977	0.04	5.03	0.0001	0.0009952	0.12	10.07	0.0003	0.0009928	0.18	15.07	0.0004
20	0.0009996	83.61	88.61	0.2954	0.0009973	83.31	93.28	0.2943	0.0009951	83.01	97.93	0.2932
40	0.0010057	166.92	171.95	0.5705	0.0010035	166.33	176.37	0.5685	0.0010013	165.75	180.77	0.5666
60	0.0010149	250.29	255.36	0.8287	0.0010127	249.43	259.55	0.8260	0.0010105	248.58	263.74	0.8234
80	0.0010267	333.82	338.96	1.0723	0.0010244	332.69	342.94	1.0691	0.0010221	331.59	346.92	1.0659
100	0.0010410	417.65	422.85	1.3034	0.0010385	416.23	426.62	1.2996	0.0010361	414.85	430.39	1.2958
120	0.0010576	501.91	507.19	1.5236	0.0010549	500.18	510.73	1.5191	0.0010522	498.50	514.28	1.5148
140	0.0010769	586.80	592.18	1.7344	0.0010738	584.72	595.45	1.7293	0.0010708	582.69	598.75	1.7243
160	0.0010988	672.55	678.04	1.9374	0.0010954	670.06	681.01	1.9316	0.0010920	667.63	684.01	1.9259
180	0.0011240	759.47	765.09	2.1338	0.0011200	756.48	767.68	2.1271	0.0011160	753.58	770.32	2.1206
200	0.0011531	847.92	853.68	2.3251	0.0011482	844.32	855.80	2.3174	0.0011435	840.84	858.00	2.3100
220	0.0011868	938.39	944.32	2.5127	0.0011809	934.01	945.82	2.5037	0.0011752	929.81	947.43	2.4951
240	0.0012268	1031.6	1037.7	2.6983	0.0012192	1026.2	1038.3	2.6876	0.0012121	1021.0	1039.2	2.6774
260	0.0012755	1128.5	1134.9	2.8841	0.0012653	1121.6	1134.3	2.8710	0.0012560	1115.1	1134.0	2.8586
280					0.0013226	1221.8	1235.0	3.0565	0.0013096	1213.4	1233.0	3.0410
300					0.0013980	1329.4	1343.3	3.2488	0.0013783	1317.6	1338.3	3.2279
320									0.0014733	1431.9	1454.0	3.4263
340									0.0016311	1567.9	1592.4	3.6555
$P = 20 \text{ MPa (365.75°C)}$					$P = 30 \text{ MPa}$				$P = 50 \text{ MPa}$			
Sat.	0.0020378	1785.8	1826.6	4.0146	0.0009857	0.29	29.86	0.0003	0.0009767	0.29	49.13	-0.0010
0	0.0009904	0.23	20.03	0.0005	0.0009886	82.11	111.77	0.2897	0.0009805	80.93	129.95	0.2845
20	0.0009929	82.71	102.57	0.2921	0.0009886	82.11	111.77	0.2897	0.0009805	80.93	129.95	0.2845
40	0.0009992	165.17	185.16	0.5646	0.0009951	164.05	193.90	0.5607	0.0009872	161.90	211.25	0.5528
60	0.0010084	247.75	267.92	0.8208	0.0010042	246.14	276.26	0.8156	0.0009962	243.08	292.88	0.8055
80	0.0010199	330.50	350.90	1.0627	0.0010155	328.40	358.86	1.0564	0.0010072	324.42	374.78	1.0442
100	0.0010337	413.50	434.17	1.2920	0.0010290	410.87	441.74	1.2847	0.0010201	405.94	456.94	1.2705
120	0.0010496	496.85	517.84	1.5105	0.0010445	493.66	525.00	1.5020	0.0010349	487.69	539.43	1.4859
140	0.0010679	580.71	602.07	1.7194	0.0010623	576.90	608.76	1.7098	0.0010517	569.77	622.36	1.6916

Reference State and Reference Values

- The values of u , h , and s cannot be measured directly, and they are calculated from measurable properties using the relations between properties
- However, those relations give the *changes* in properties, not the values of properties at specified states
- Therefore, we need to choose a convenient *reference state* and assign a value of *zero* for a convenient property or properties at that state
- Some properties may have negative values as a result of the reference state chosen
- Sometimes different tables list different values for some properties at the same state as a result of using a different reference state
- However, In thermodynamics we are concerned with the *changes* in properties, and the reference state chosen is of no consequence in calculations

Reference State and Reference Values

Saturated water—Temperature table A-4

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg} \cdot \text{K}$		
		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
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

Saturated refrigerant-134a—Temperature table A-11

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, $\text{kJ/kg} \cdot \text{K}$		
		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
-40	51.25	0.0007054	0.36081	-0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

- The reference state for water is 0.01°C and for R-134a is -40°C in tables
- Note that $h = u + Pv$, hence both h and u cannot be simultaneously zero due to finite pressure (P) and specific volume (v) terms

THE IDEAL-GAS EQUATION OF STATE

- **Equation of state**: Any equation that relates the pressure, temperature, and specific volume of a substance
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the P - v - T behavior of a gas quite accurately within some properly selected region

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

$$Pv = RT$$

Ideal gas equation of state

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

Different substances have
different gas constants

UNIVERSAL GAS CONSTANT


$$Pv = RT$$

$$R = \frac{R_u}{M} \quad (\text{kJ/kg} \cdot \text{K} \text{ or } \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

R : gas constant

M : molar mass (kg/kmol)

R_u : universal gas constant

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


Mass = Molar mass \times Mole number

$$m = MN \quad (\text{kg})$$

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

Ideal gas equation at two states for a fixed mass

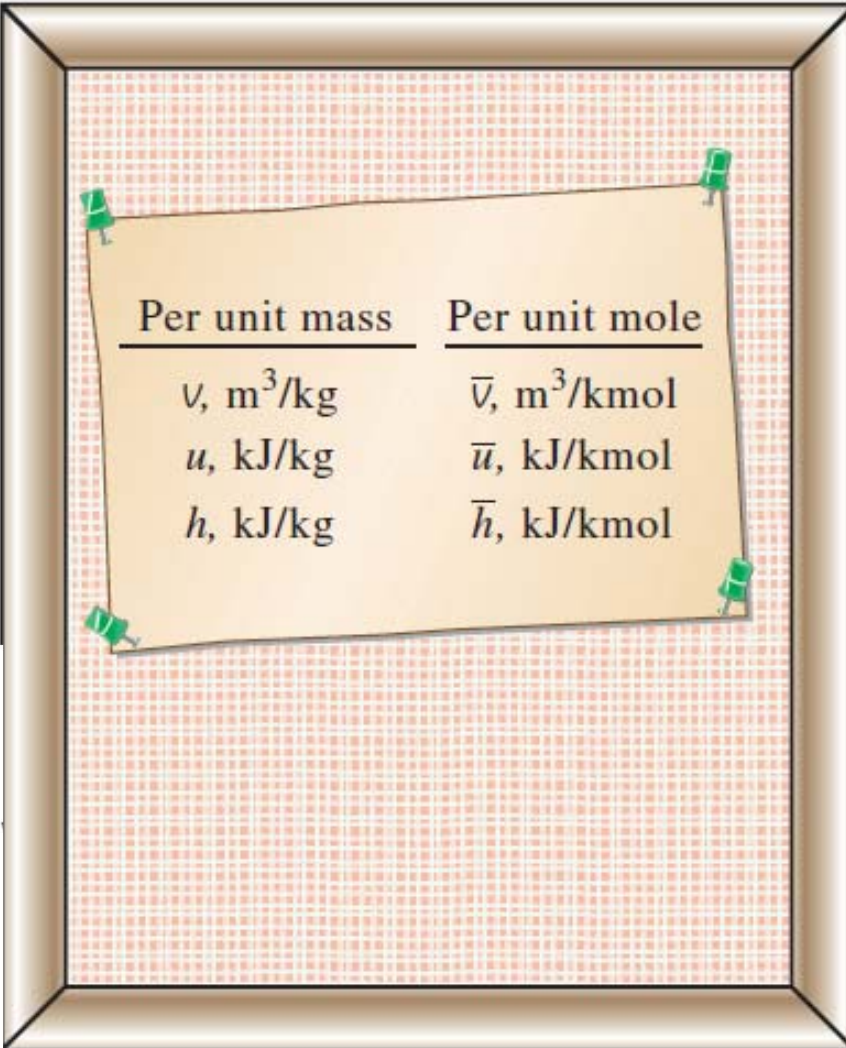
Various expressions
of ideal gas equation

$$V = m\upsilon \longrightarrow PV = mRT$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_u T$$

$$V = N\bar{V} \longrightarrow P\bar{V} = R_u T$$

- Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature)

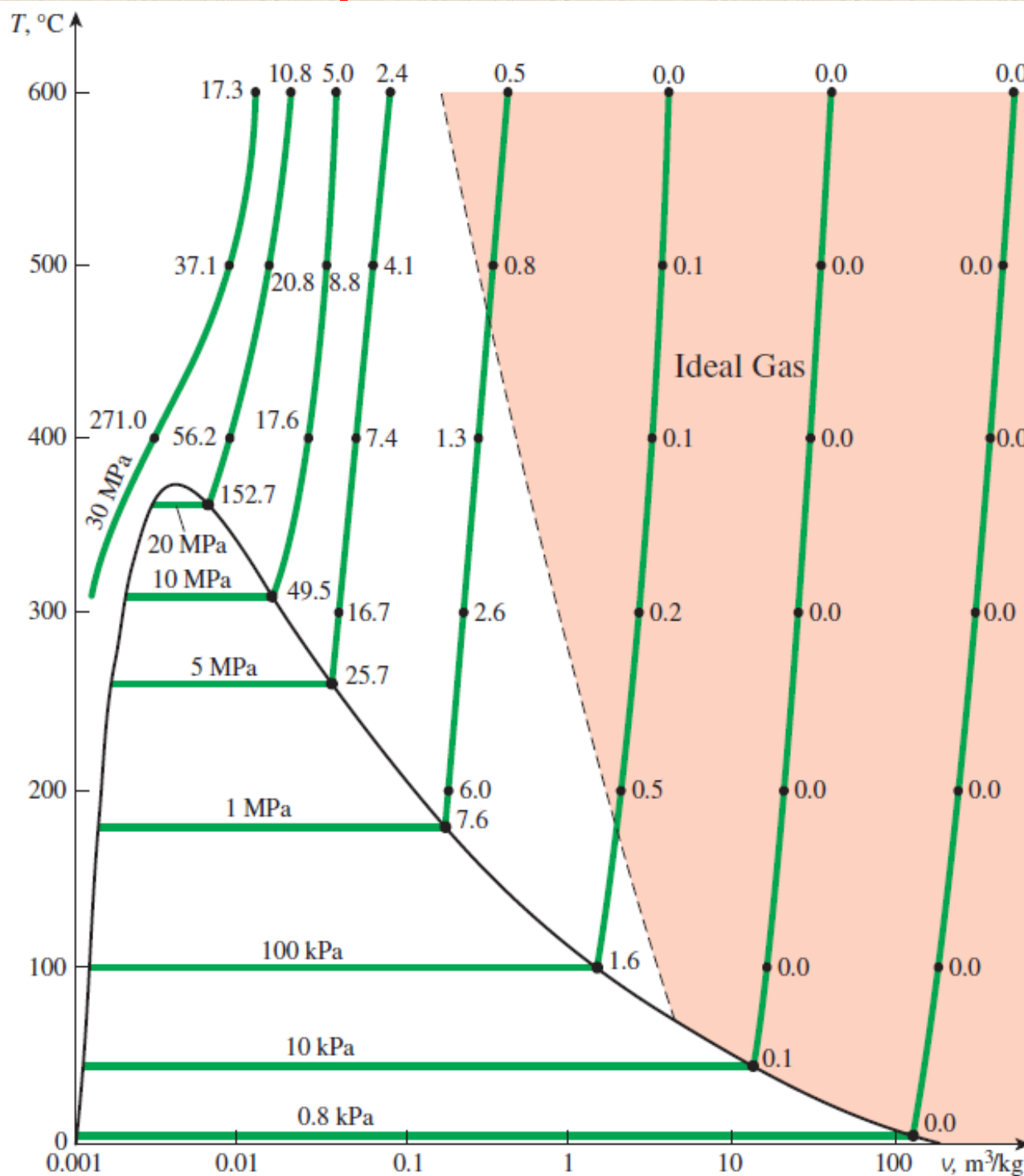


Per unit mass	Per unit mole
$\upsilon, \text{m}^3/\text{kg}$	$\bar{\upsilon}, \text{m}^3/\text{kmol}$
$u, \text{kJ/kg}$	$\bar{u}, \text{kJ/kmol}$
$h, \text{kJ/kg}$	$\bar{h}, \text{kJ/kmol}$

FIGURE 3–43

Properties per unit mole are denoted with a bar on the top.

Is Water Vapor an Ideal Gas?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent)
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line

Percentage of error

$$\left(\frac{|v_{\text{table}} - v_{\text{ideal}}|}{v_{\text{table}}} \times 100 \right)$$
 involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

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

- **Compressibility factor Z :** A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.
- The farther away Z is from unity, the more the gas deviates from ideal-gas behavior

$$Pv = ZRT$$

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

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

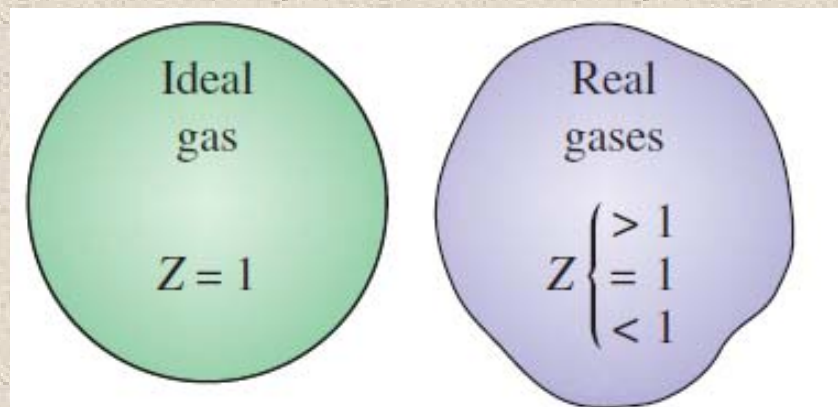
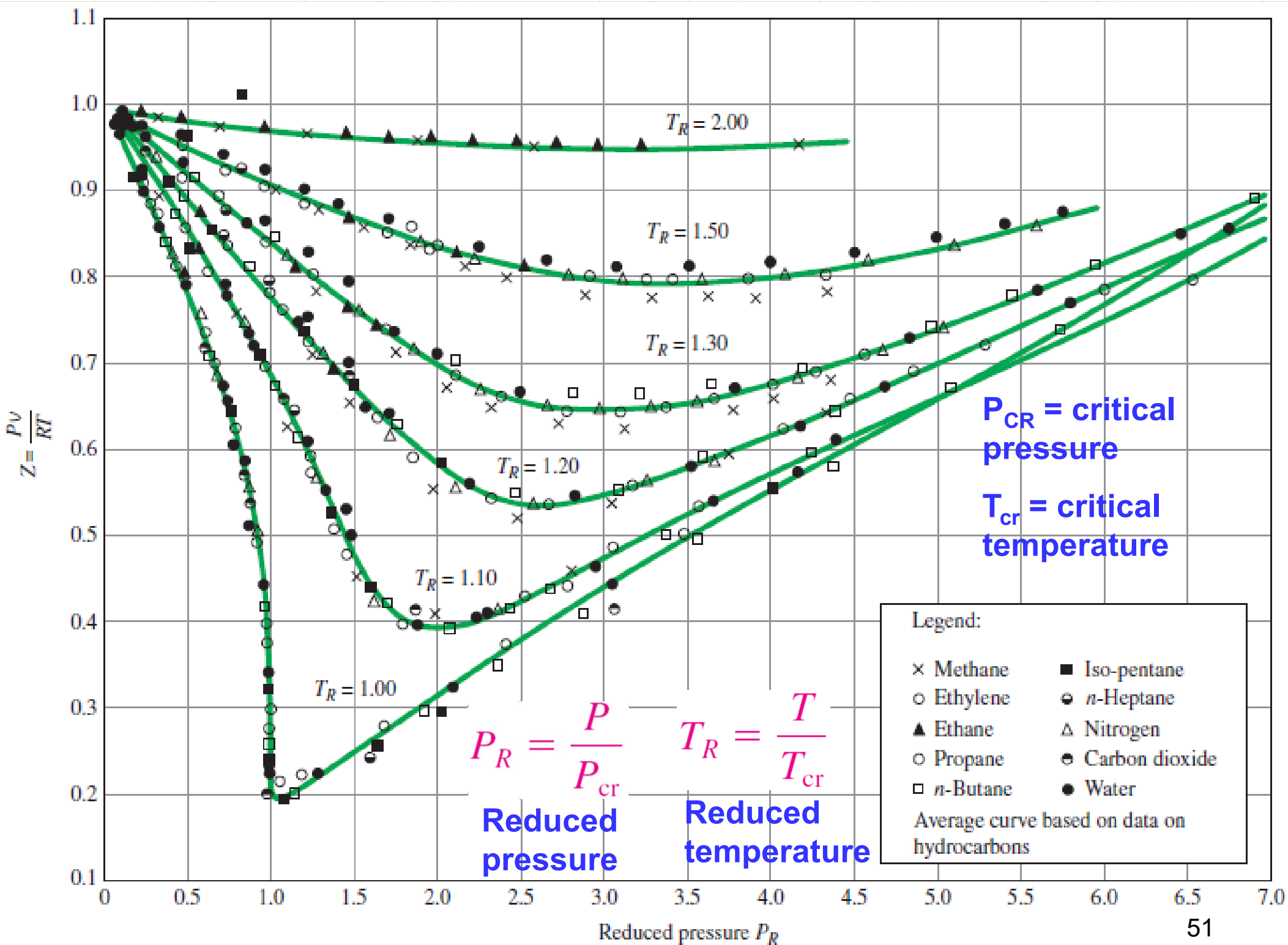


FIGURE 3–46

The compressibility factor is unity for ideal gases.



DEVIATION FROM IDEAL-GAS BEHAVIOR

- At low pressures ($P_R \ll 1$), gases behave as an ideal gas regardless of temperature
- At high temperature ($T_R > 2$), ideal-gas behavior can be assumed regardless of pressure (except when $PR \gg 1$)
- The deviation of a gas from ideal-gas behavior is greatest in the vicinity of the critical point

DEVIATION FROM IDEAL-GAS BEHAVIOR

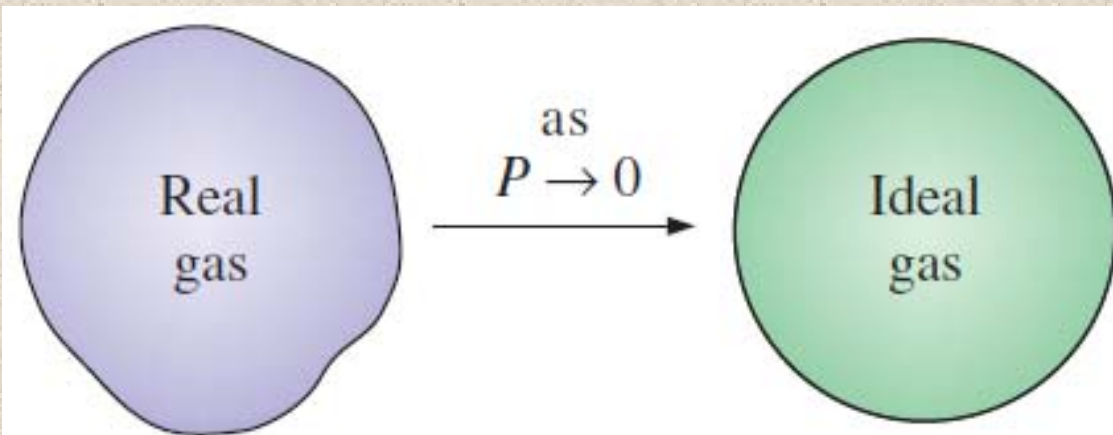


FIGURE 3–48

At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

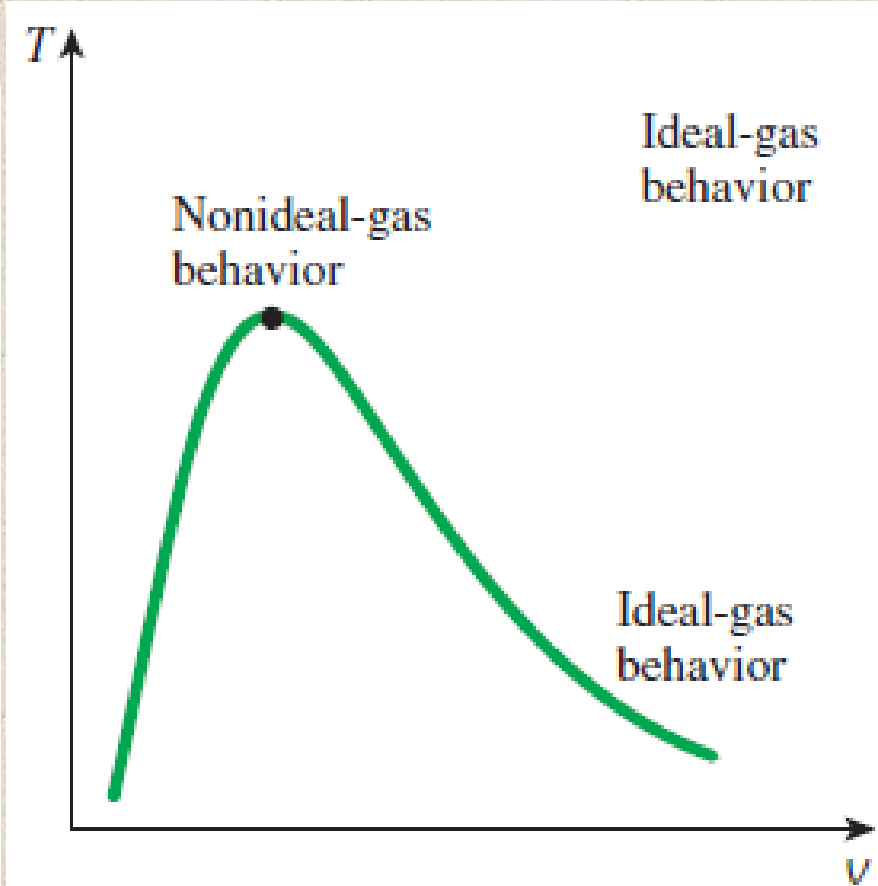


FIGURE 3–49

Gases deviate from the ideal-gas behavior the most in the neighborhood of the critical point.

OTHER EQUATIONS OF STATE

- Several equations have been proposed to represent the P - v - T behavior of substances accurately over a larger region with no limitations.

van der Waals

Berthelet

Redlich-Kwang

Beattie-Bridgeman

Benedict-Webb-Rubin

Strobridge

Virial

Van der Waals Equation of State

$$\left(P + \frac{a}{v^2} \right) (v - b) = RT$$

$$a = \frac{27R^2T_{\text{cr}}^2}{64P_{\text{cr}}} \quad b = \frac{RT_{\text{cr}}}{8P_{\text{cr}}}$$

- This model includes two effects not considered in the ideal-gas model: the *intermolecular attraction forces* (a/v^2 term) and the *volume occupied by the molecules themselves* (b term)

Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{v}^2} \left(1 - \frac{c}{\bar{v} T^3} \right) (\bar{v} + B) - \frac{A}{\bar{v}^2}$$

$$A = A_0 \left(1 - \frac{a}{\bar{v}} \right) \quad B = B_0 \left(1 - \frac{b}{\bar{v}} \right)$$

The constants are given in Table 3–4 for various substances. It is known to be reasonably accurate for densities up to about $0.8\rho_{\text{cr}}$.

Benedict-Webb-Rubin Equation of State

$$P = \frac{R_u T}{\bar{V}} + \left(B_0 R_u T - A_0 - \frac{C_0}{T^2} \right) \frac{1}{\bar{V}^2} + \frac{b R_u T - a}{\bar{V}^3} + \frac{a \alpha}{\bar{V}^6} + \frac{c}{\bar{V}^3 T^2} \left(1 + \frac{\gamma}{\bar{V}^2} \right) e^{-\gamma/\bar{V}^2}$$

The constants are given in Table 3–4. This equation can handle substances at densities up to about $2.5 \rho_{\text{cr}}$.

Virial Equation of State

$$P = \frac{RT}{V} + \frac{a(T)}{V^2} + \frac{b(T)}{V^3} + \frac{c(T)}{V^4} + \frac{d(T)}{V^5} + \dots$$

The coefficients $a(T)$, $b(T)$, $c(T)$, and so on, that are functions of temperature alone are called *virial coefficients*. These coefficients can be determined experimentally or theoretically from statistical mechanics

TABLE 3–4

Constants that appear in the Beattie-Bridgeman and the Benedict-Webb-Rubin equations of state

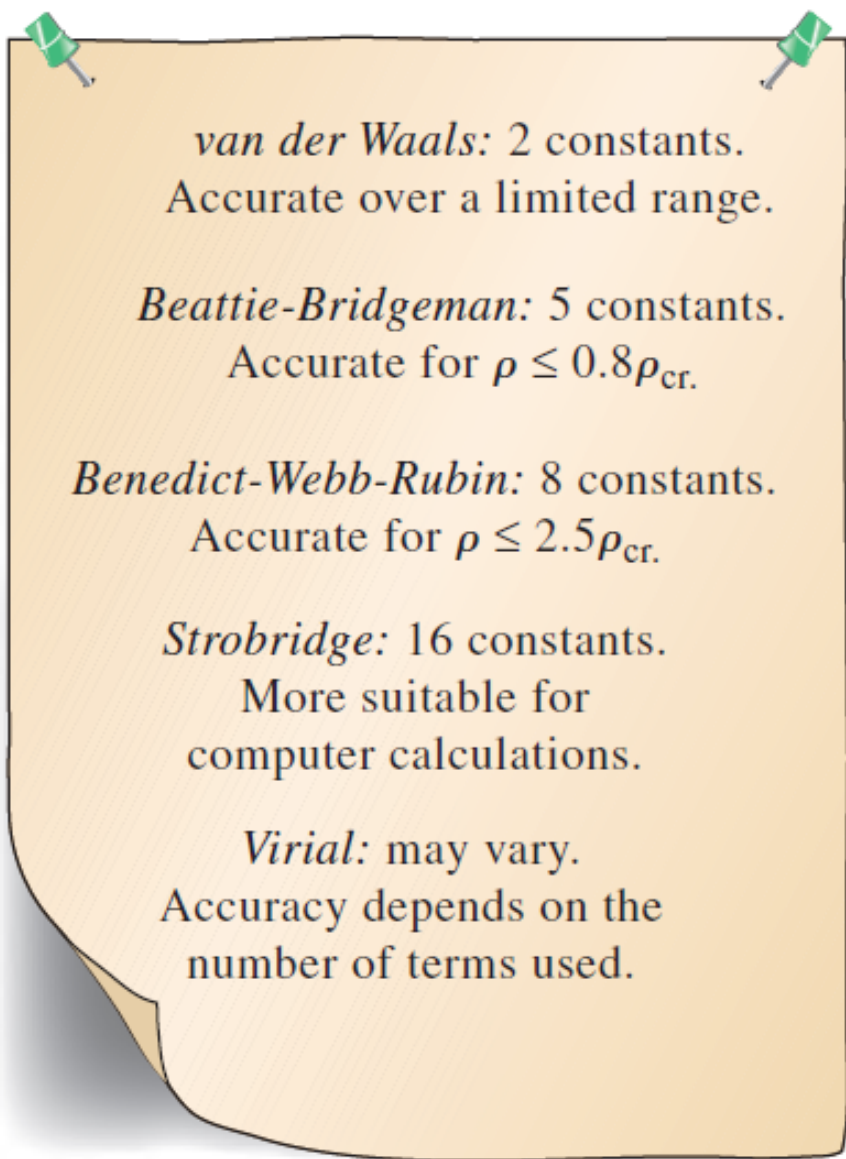
(a) When P is in kPa, \bar{v} is in m^3/kmol , T is in K, and $R_u = 8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K}$, the five constants in the Beattie-Bridgeman equation are as follows:

Gas	A_0	a	B_0	b	c
Air	131.8441	0.01931	0.04611	-0.001101	4.34×10^4
Argon, Ar	130.7802	0.02328	0.03931	0.0	5.99×10^4
Carbon dioxide, CO_2	507.2836	0.07132	0.10476	0.07235	6.60×10^5
Helium, He	2.1886	0.05984	0.01400	0.0	40
Hydrogen, H_2	20.0117	-0.00506	0.02096	-0.04359	504
Nitrogen, N_2	136.2315	0.02617	0.05046	-0.00691	4.20×10^4
Oxygen, O_2	151.0857	0.02562	0.04624	0.004208	4.80×10^4

Source: Gordon J. Van Wylen and Richard E. Sonntag, *Fundamentals of Classical Thermodynamics*, English/SI Version, 3rd ed. (New York: John Wiley & Sons, 1986), p. 46, table 3.3.

(b) When P is in kPa, \bar{v} is in m^3/kmol , T is in K, and $R_u = 8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K}$, the eight constants in the Benedict-Webb-Rubin equation are as follows:

Gas	a	A_0	b	B_0	c	C_0	α	γ
n-Butane, C_4H_{10}	190.68	1021.6	0.039998	0.12436	3.205×10^7	1.006×10^8	1.101×10^{-3}	0.0340
Carbon dioxide, CO_2	13.86	277.30	0.007210	0.04991	1.511×10^6	1.404×10^7	8.470×10^{-5}	0.00539
Carbon monoxide, CO	3.71	135.87	0.002632	0.05454	1.054×10^5	8.673×10^5	1.350×10^{-4}	0.0060
Methane, CH_4	5.00	187.91	0.003380	0.04260	2.578×10^5	2.286×10^6	1.244×10^{-4}	0.0060
Nitrogen, N_2	2.54	106.73	0.002328	0.04074	7.379×10^4	8.164×10^5	1.272×10^{-4}	0.0053



van der Waals: 2 constants.
Accurate over a limited range.

Beattie-Bridgeman: 5 constants.
Accurate for $\rho \leq 0.8\rho_{\text{cr}}$.

Benedict-Webb-Rubin: 8 constants.
Accurate for $\rho \leq 2.5\rho_{\text{cr}}$.

Strobridge: 16 constants.
More suitable for
computer calculations.

Virial: may vary.
Accuracy depends on the
number of terms used.

FIGURE 3–55

Complex equations of state represent the P - v - T behavior of gases more accurately over a wider range.

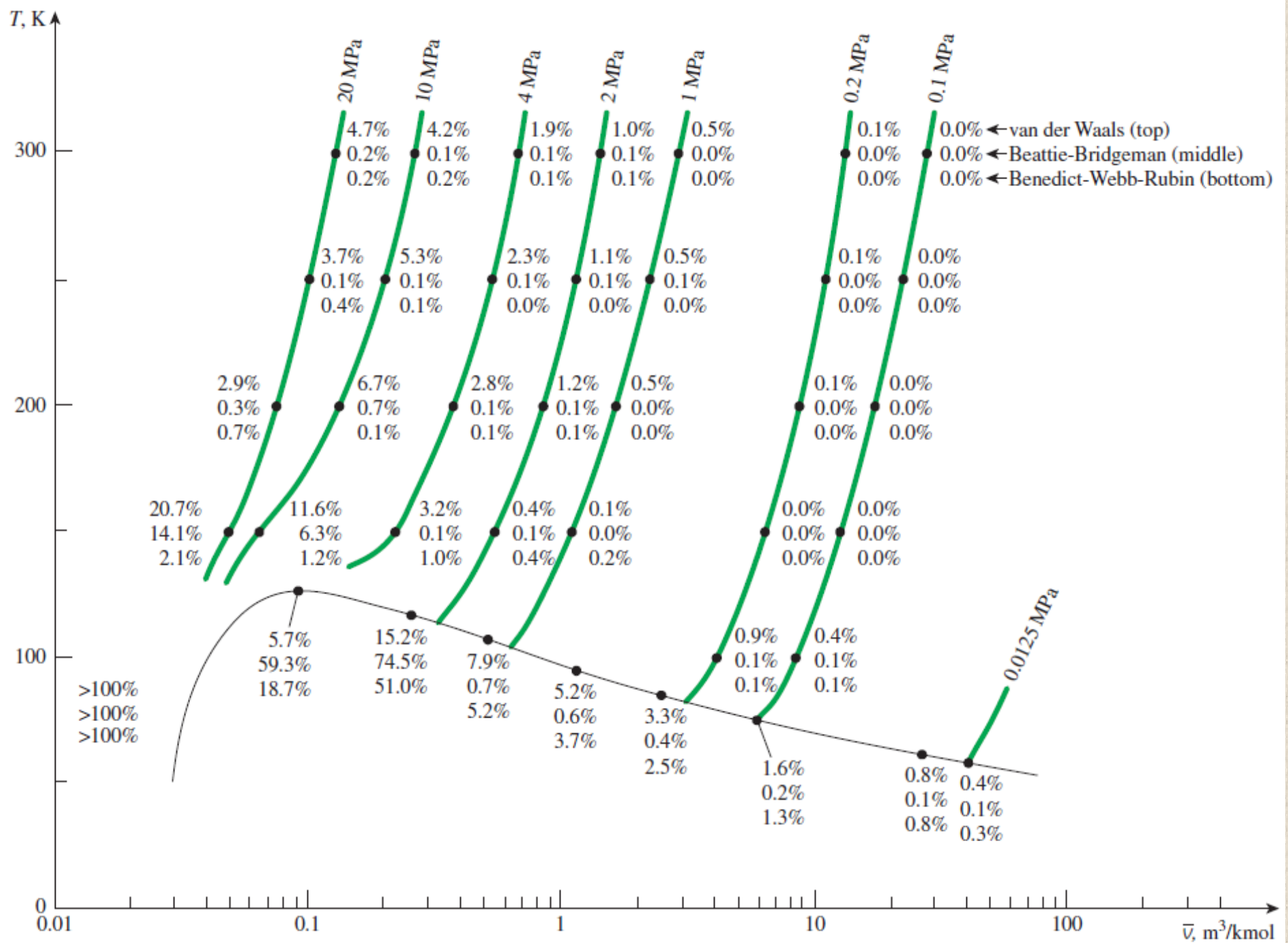


FIGURE 3-56

Percentage of error involved in various equations of state for nitrogen (% error = $[(v_{\text{table}} - v_{\text{equation}})/v_{\text{table}}] \times 100$).

Summary

- Pure substance
- Phases of a pure substance
- Phase-change processes of pure substances
 - ✓ Compressed liquid, Saturated liquid, Saturated vapor, Superheated vapor
 - ✓ Saturation temperature and Saturation pressure
- Property diagrams for phase change processes
 - ✓ The T - v diagram, The P - v diagram, The P - T diagram, The P - v - T surface
- Property tables
 - ✓ Enthalpy
 - ✓ Saturated liquid, saturated vapor, Saturated liquid vapor mixture, Superheated vapor, compressed liquid
 - ✓ Reference state and reference values
- The ideal gas equation of state
 - ✓ Is water vapor an ideal gas?
- Compressibility factor
- Other equations of state
 - ✓ van der Waals Equation of State, Beattie-Bridgeman Equation of State
 - ✓ Benedict-Webb-Rubin Equation of State, Virial Equation of State