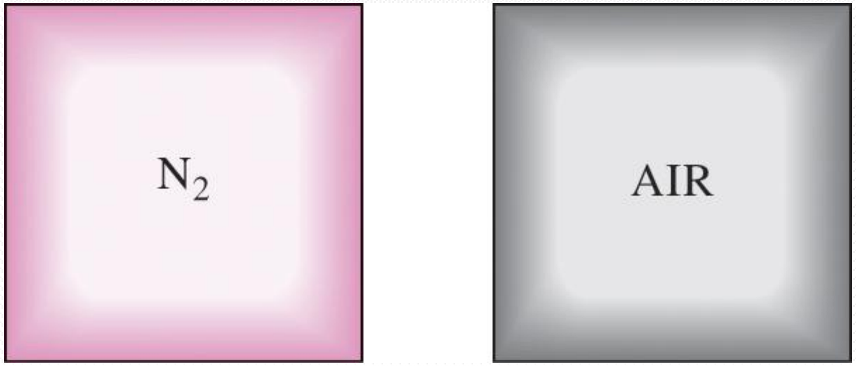
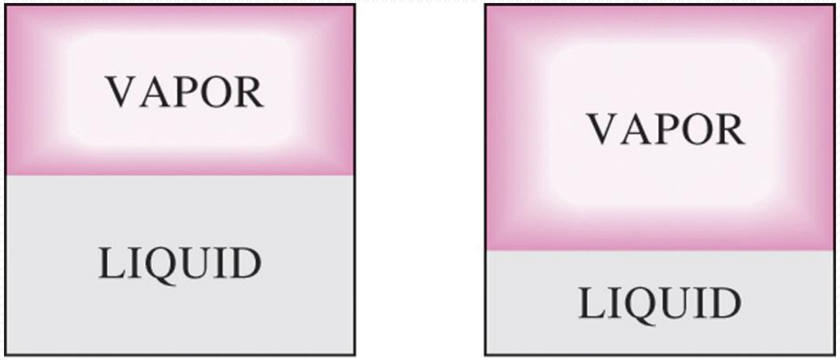
Chapter 3 Properties of A Pure Substance

- **Pure substance**: A pure substance is one that has a homogeneous and invariable chemical composition.
- Air is a mixture of several gases, but it is considered to be a pure substance.



Nitrogen and gaseous air are pure substances.

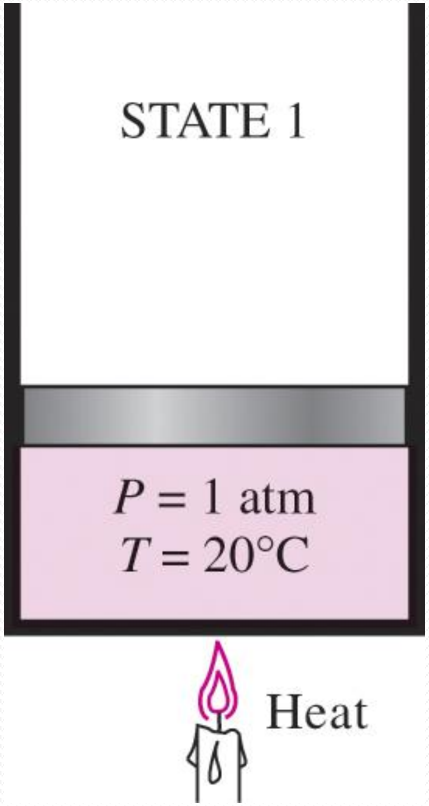


(*a*) H_2O (*b*) AIR

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

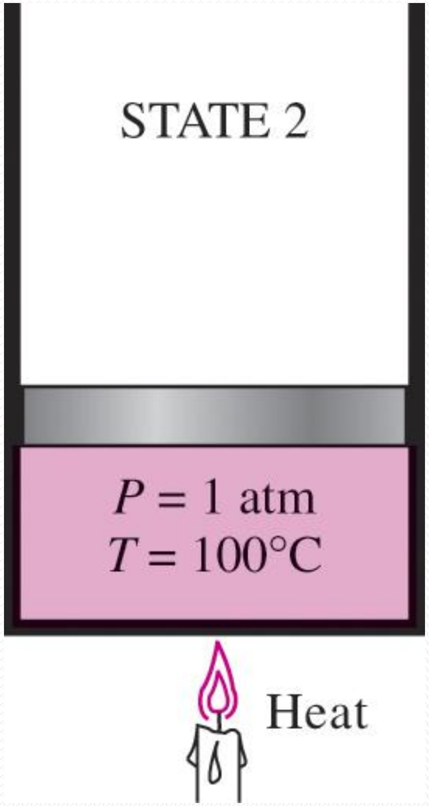
PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

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

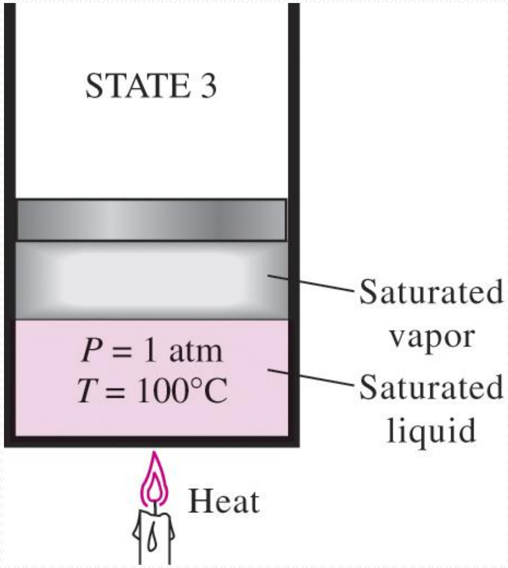


At 1 atm and 20°C, water exists in the liquid phase (***compressed liquid***).

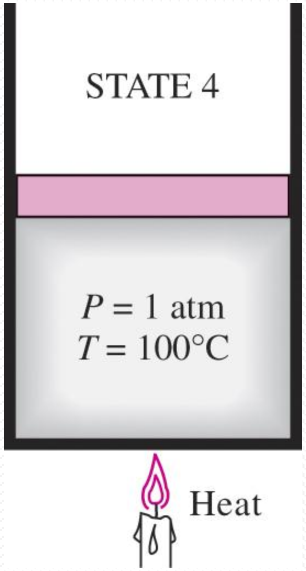
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (***saturated liquid***).



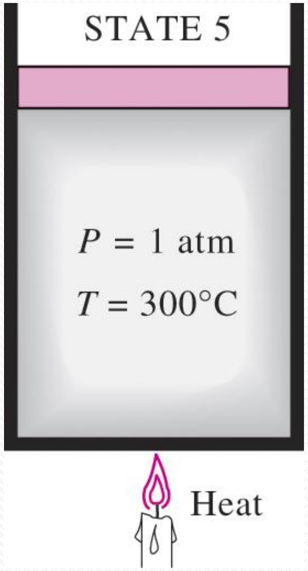
- **Saturated vapor**: A vapor that is *about to condense*.
- **Saturated liquid–vapor mixture**: The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor**: A vapor that is *not about to condense* (i.e., not a saturated vapor).



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***).



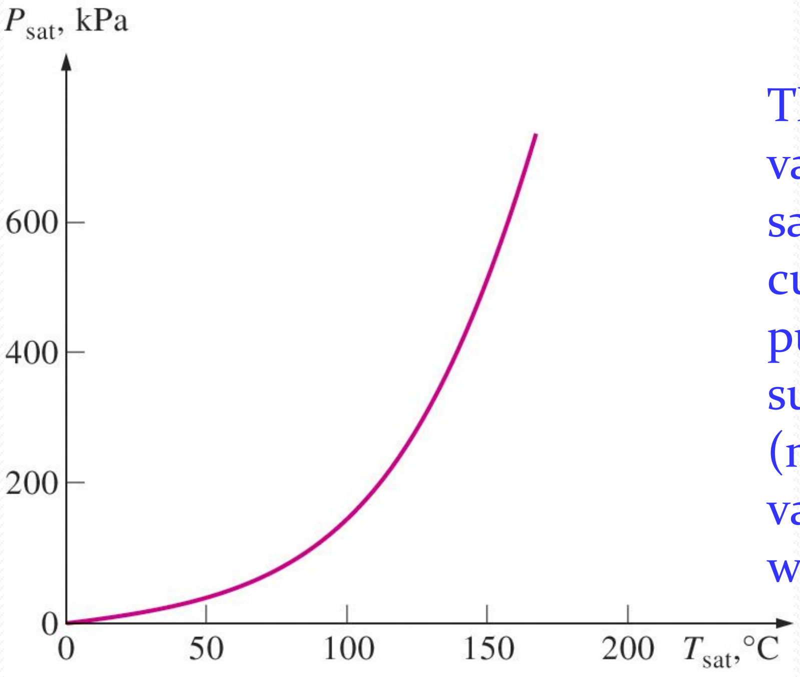
As more heat is transferred, the temperature of the vapor starts to rise (***superheated vapor***).

Saturation Temperature and Saturation Pressure

The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

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

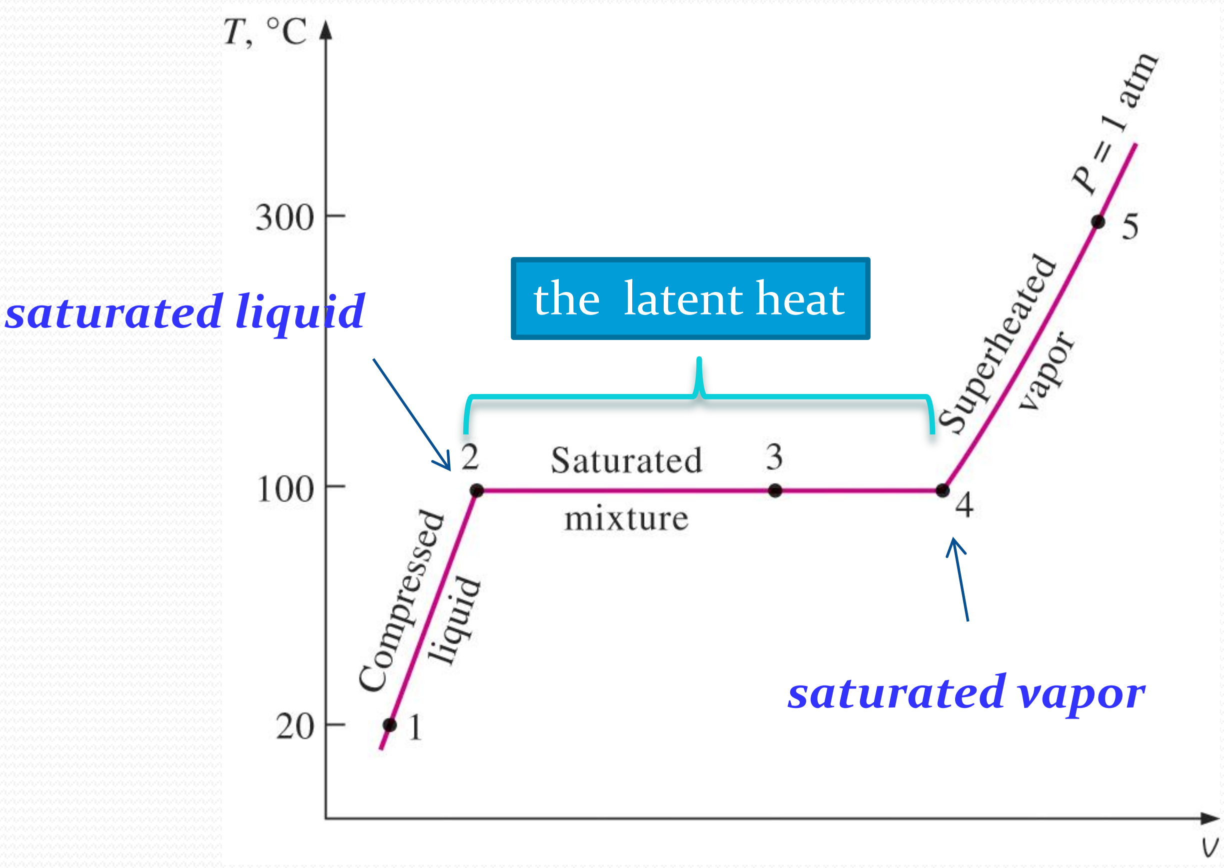
Saturation pressure P_{sat}: The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

Saturation (boiling) pressure of water at various temperatures

Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

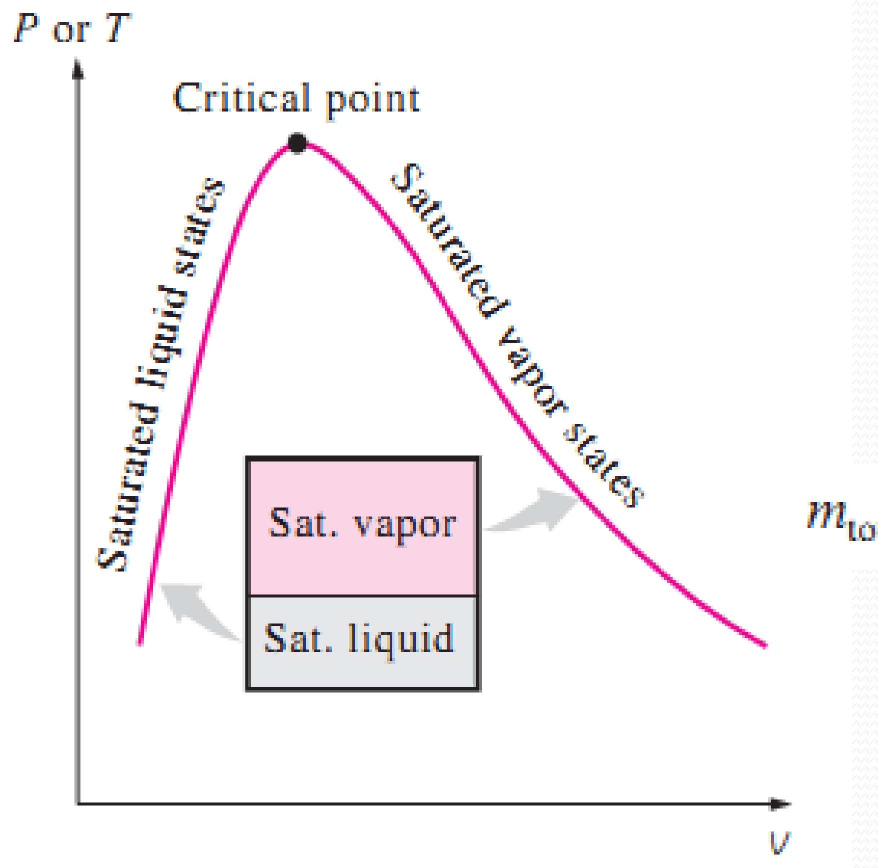


saturated liquid

the latent heat

saturated vapor

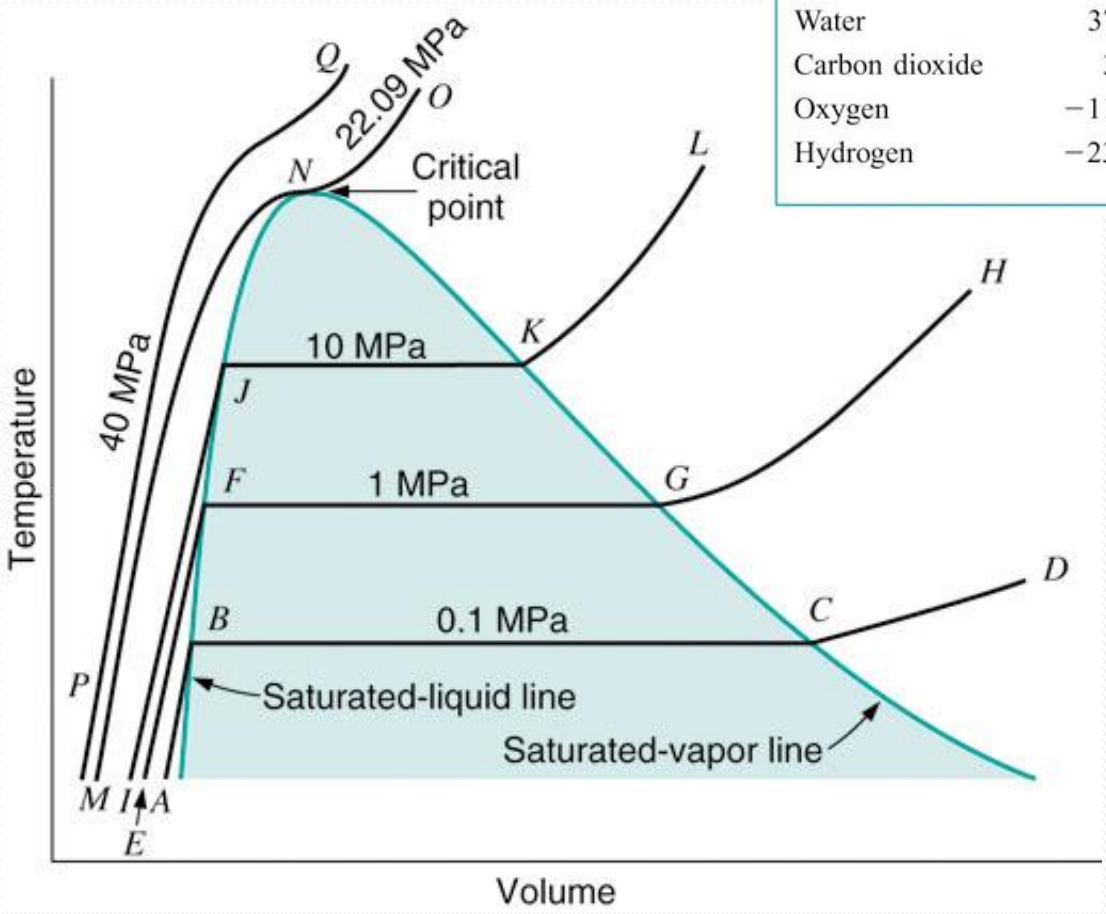
T-*v* diagram for the heating process of water at constant pressure.



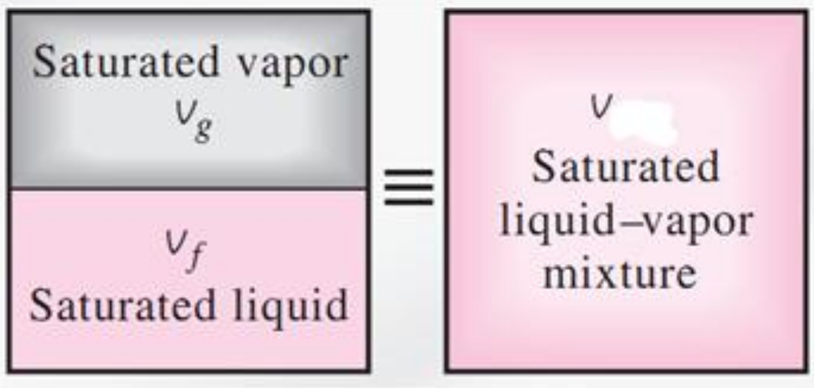
$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}}$$

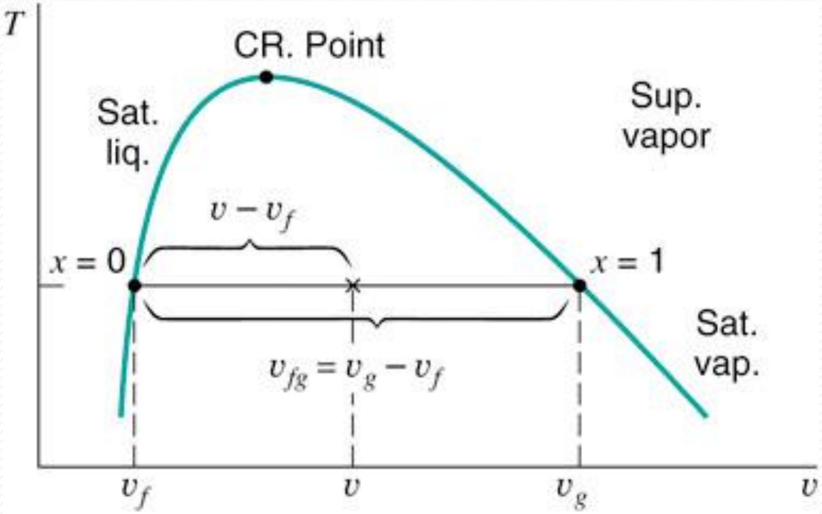
$$m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

	Critical Temperature, °C	Critical Pressure, MPa	Critical Volume, m^3/kg
Water	374.14	22.09	0.003 155
Carbon dioxide	31.05	7.39	0.002 143
Oxygen	−118.35	5.08	0.002 438
Hydrogen	−239.85	1.30	0.032 192



The critical-point data for more substances are given in Aksel’s Table 2.1.





$$V = V_{liq} + V_{vap} = m_{liq} v_f + m_{vap} v_g$$

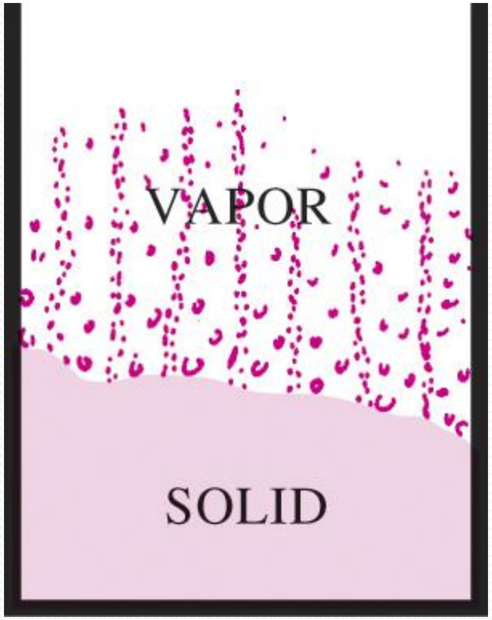
$$v = \frac{V}{m} = \frac{m_{liq}}{m} v_f + \frac{m_{vap}}{m} v_g = (1 - x) v_f + x v_g$$

$$v_{fg} = v_g - v_f$$

$$v = v_f + x v_{fg} \qquad (m^3/kg)$$

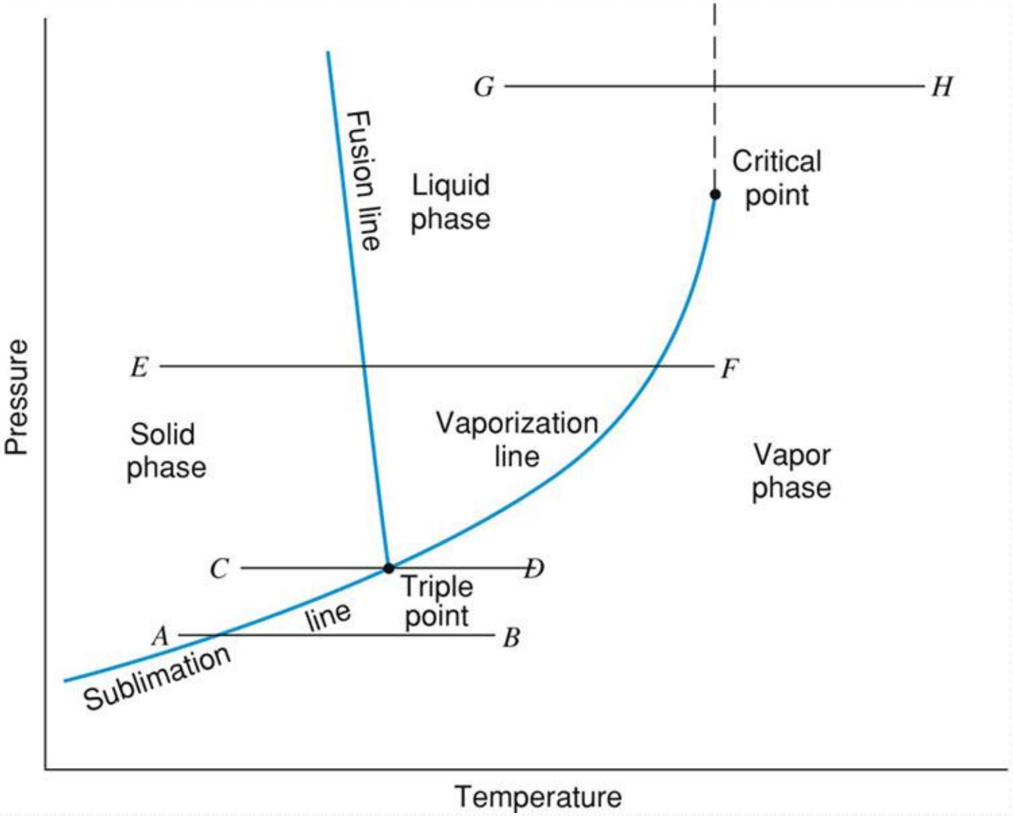
$$x = \frac{v_{avg} - v_f}{v_{fg}}$$

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



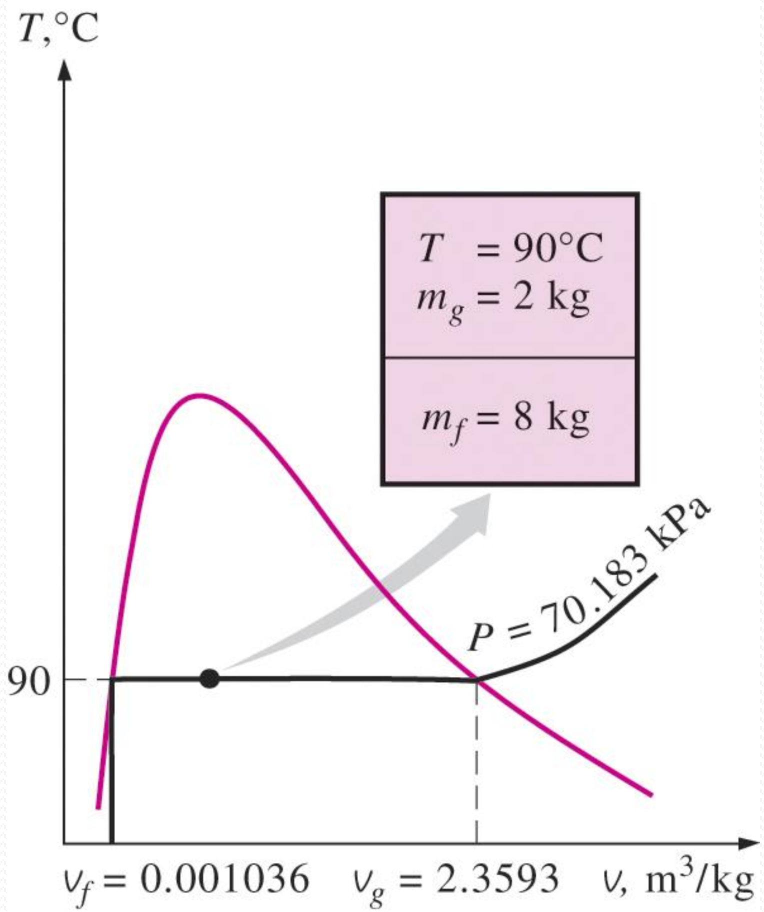
At low pressures (below the triple-point value), solids evaporate without melting first (*sublimation*).

Phase Diagram



P-T diagram of pure substances.

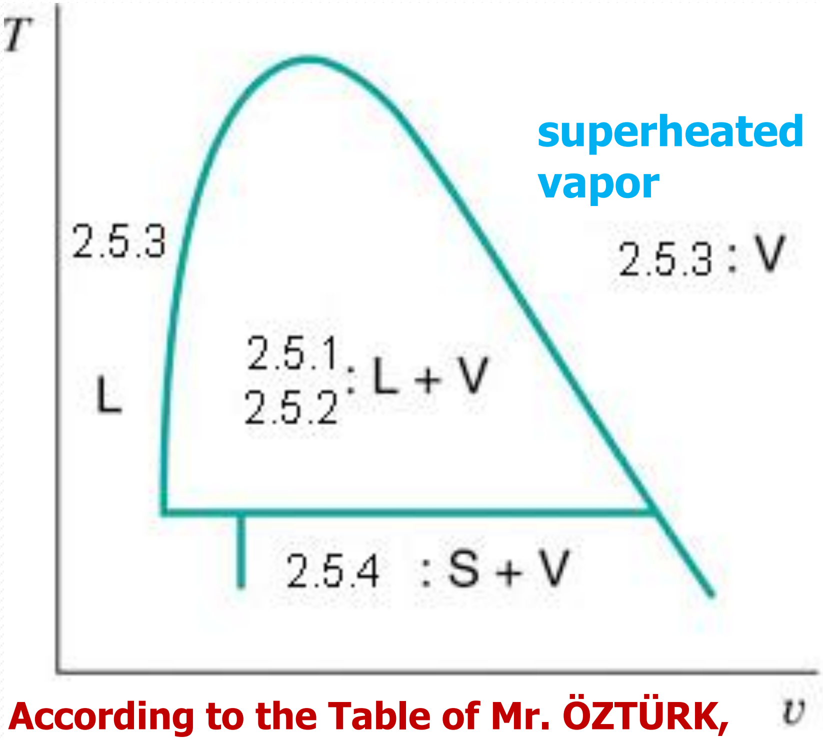
Independent Properties of a Pure Substance

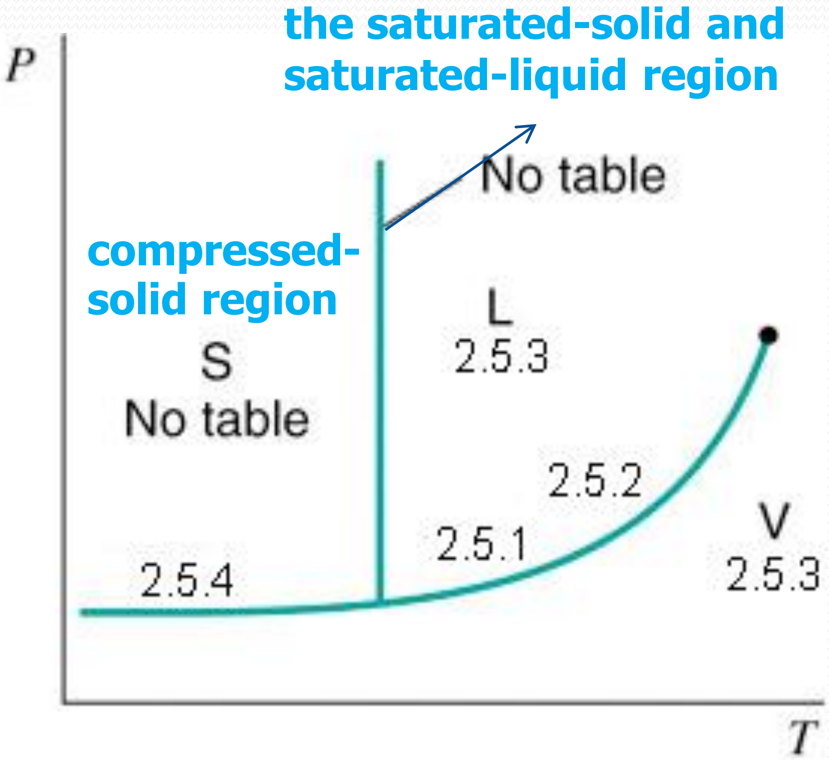


The state is fixed by any two independent, intensive properties

In a saturation state, pressure and temperature are not independent properties.

Tables of Thermodynamic Properties





According to the Table of Mr. ÖZTÜRK,

Superheated vapor and compressed liquid is given in Table 2.5.3 between 29 and 37.

The saturated-liquid and saturated-vapor region is listed according to the *saturated temperature* in Table 2.5.1 between 24 and 26 and according to the *saturated pressure* in Table2.5.2 on pages 27 and 28.

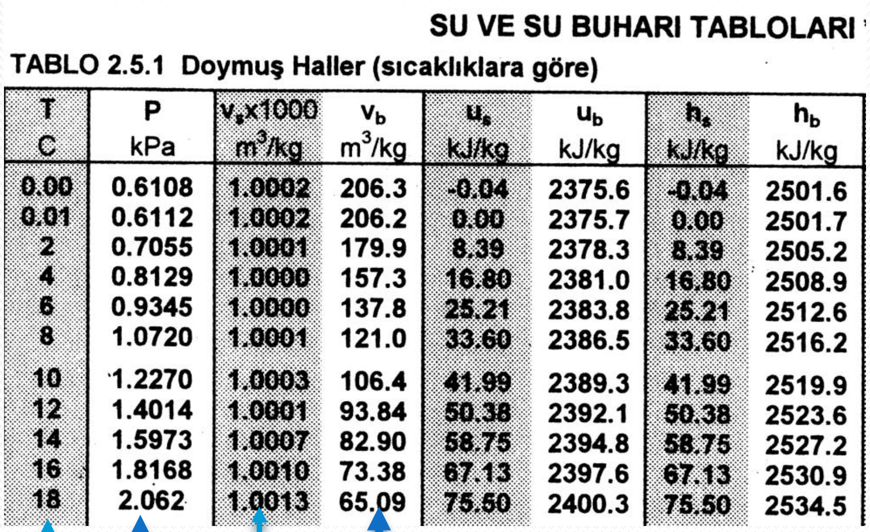
The saturated-solid and saturated-vapor region is listed according to *temperature* in Table 2.5.4 on page 38

Saturated Liquid and Saturated Vapor States

Table 2.5.1 Saturation properties of water under temperature.

Table 2.5.2 Saturation properties of water under pressure.

A partial list of Table 2.5.1



SU VE SU BUHARI TABLOLARI

TABLO 2.5.1 Doymuş Haller (sıcaklıklara göre)

T C	P kPa	v_sx1000 m^3/kg	v_b m^3/kg	u_s kJ/kg	u_b kJ/kg	h_s kJ/kg	h_b kJ/kg
0.00	0.6108	1.0002	206.3	-0.04	2375.6	-0.04	2501.6
0.01	0.6112	1.0002	206.2	0.00	2375.7	0.00	2501.7
2	0.7055	1.0001	179.9	8.39	2378.3	8.39	2505.2
4	0.8129	1.0000	157.3	16.80	2381.0	16.80	2508.9
6	0.9345	1.0000	137.8	25.21	2383.8	25.21	2512.6
8	1.0720	1.0001	121.0	33.60	2386.5	33.60	2516.2
10	1.2270	1.0003	106.4	41.99	2389.3	41.99	2519.9
12	1.4014	1.0001	93.84	50.38	2392.1	50.38	2523.6
14	1.5973	1.0007	82.90	58.75	2394.8	58.75	2527.2
16	1.8168	1.0010	73.38	67.13	2397.6	67.13	2530.9
18	2.062	1.0013	65.09	75.50	2400.3	75.50	2534.5

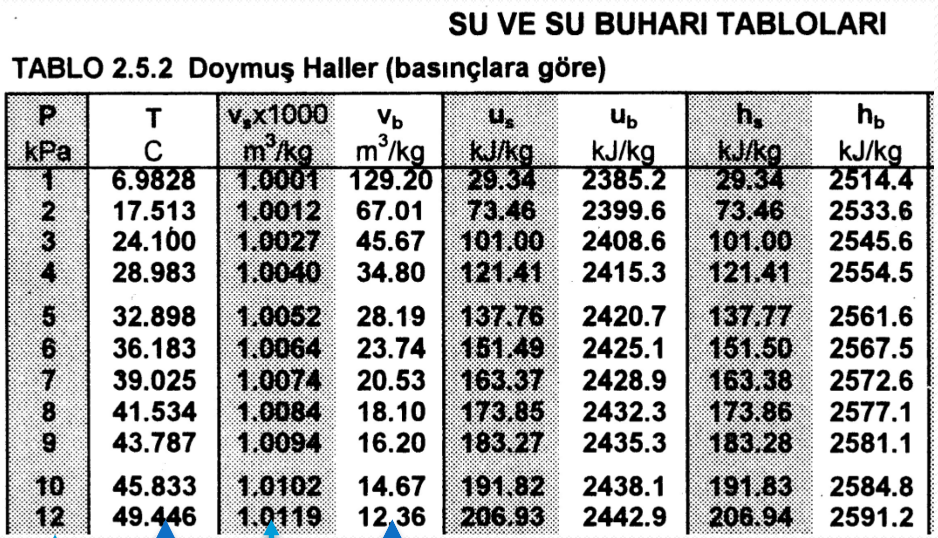
Saturated Temperature

Saturation pressure at the given saturation temperature

Specific Volume of Saturated Liquid*1000

Specific Volume of Saturated Vapor

A partial list of Table 2.5.2



SU VE SU BUHARI TABLOLARI

TABLO 2.5.2 Doymuş Haller (basınçlara göre)

P kPa	T C	v_sx1000 m^3/kg	v_b m^3/kg	u_s kJ/kg	u_b kJ/kg	h_s kJ/kg	h_b kJ/kg
1	6.9828	1.0001	129.20	29.34	2385.2	29.34	2514.4
2	17.513	1.0012	67.01	73.46	2399.6	73.46	2533.6
3	24.100	1.0027	45.67	101.00	2408.6	101.00	2545.6
4	28.983	1.0040	34.80	121.41	2415.3	121.41	2554.5
5	32.898	1.0052	28.19	137.76	2420.7	137.77	2561.6
6	36.183	1.0064	23.74	151.49	2425.1	151.50	2567.5
7	39.025	1.0074	20.53	163.37	2428.9	163.38	2572.6
8	41.534	1.0084	18.10	173.85	2432.3	173.86	2577.1
9	43.787	1.0094	16.20	183.27	2435.3	183.28	2581.1
10	45.833	1.0102	14.67	191.82	2438.1	191.83	2584.8
12	49.446	1.0119	12.36	206.93	2442.9	206.94	2591.2

Saturated Pressure

Saturation temperature at the given saturation pressure

Specific Volume of Saturated Liquid*1000

Specific Volume of Saturated Vapor

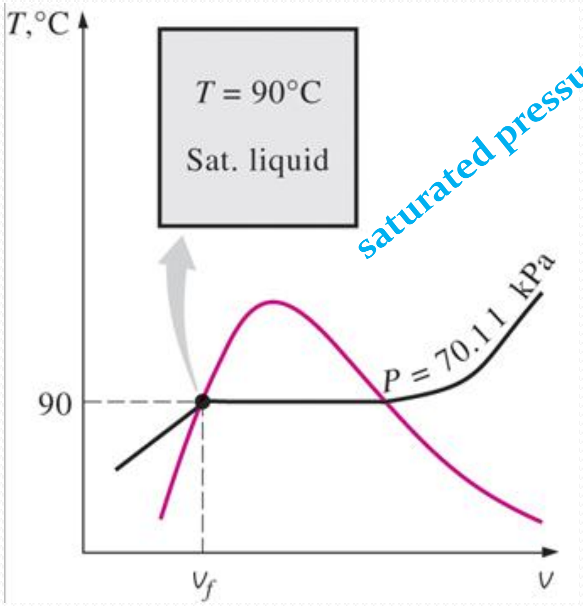
Quality is between 0 and 1 for saturated liquid–vapor mixture region or two phase region or wet region

0: satureted liquid,

1: satureted vapor.

Using of Table 2.5.1

What are the saturated pressure, specific volume of liquid and vapor at 90°C saturated temperature?



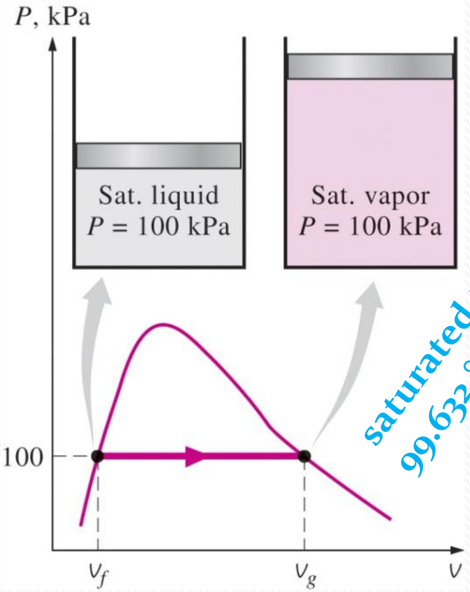
saturated pressure

specific volume of liquid, $V_s=V_f=1.0361 * 10^{-3}$ (m³/kg)

specific volume of vapor, $V_b=V_g=2.361$ (m³/kg)

Using of Table 2.5.2

What are the saturated temperature, specific volume of liquid and vapor at 100 kPa saturated pressure?

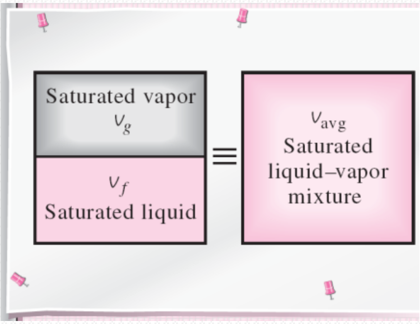


saturated temperature 99.632 °C

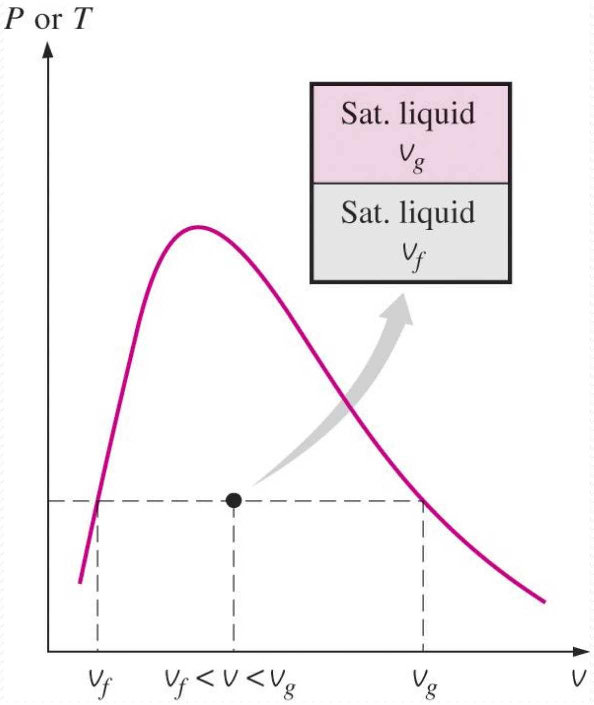
specific volume of liquid, $V_s=V_f=1.0434 * 10^{-3}$ (m³/kg)

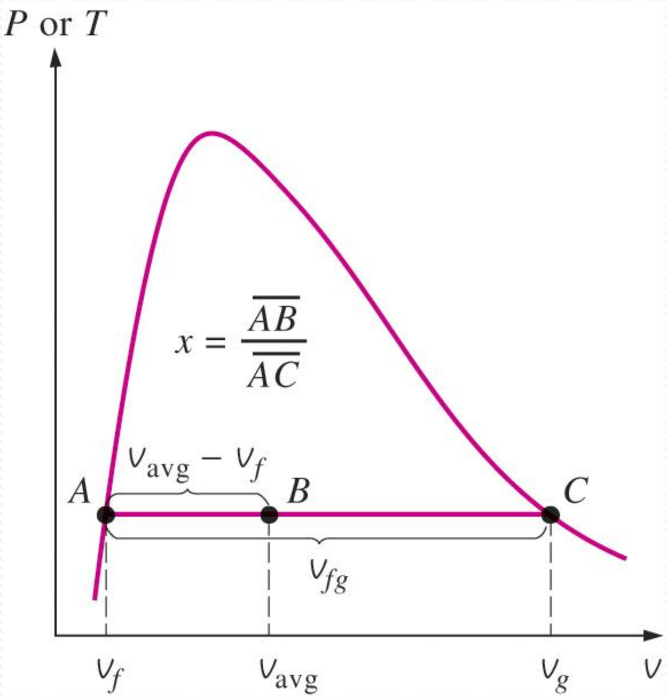
specific volume of vapor, $V_b=V_g=1.694$ (m³/kg)

Saturated Liquid–Vapor Mixture



Temperature and pressure are dependent properties for a mixture so we need a second independent property to define the state for Saturated Liquid–Vapor Mixture region.





As an example, let us calculate the specific volume of saturated steam at 200°C having a quality of 70 %.

specific volume of liquid, $V_s = V_f = 1.1565 * 10^{-3}$ (m^3/s)

specific volume of vapor, $V_b = V_g = 0.1272$ (m^3/s)

$$v_{fg} = v_g - v_f$$

$V_{fg} = 0.126044$ (m^3/s)

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

$V = 0.089387$ (m^3/s)

or

$$v = v_f + x v_{fg} = v_f + x(v_g - v_f)$$

$$v = 1.1565x10^{-3} + 0.7 * (0.1272 - 1.1565x10^{-3}) = 0.0894\, m^3 / kg$$

You can find the other properties in the table with a given quality by using same way.

y → *v, u, h, or s.*

$$y_f \leq y_{\text{avg}} \leq y_g$$

$$y_{\text{avg}} = y_f + x y_{fg}$$

Superheated Vapor

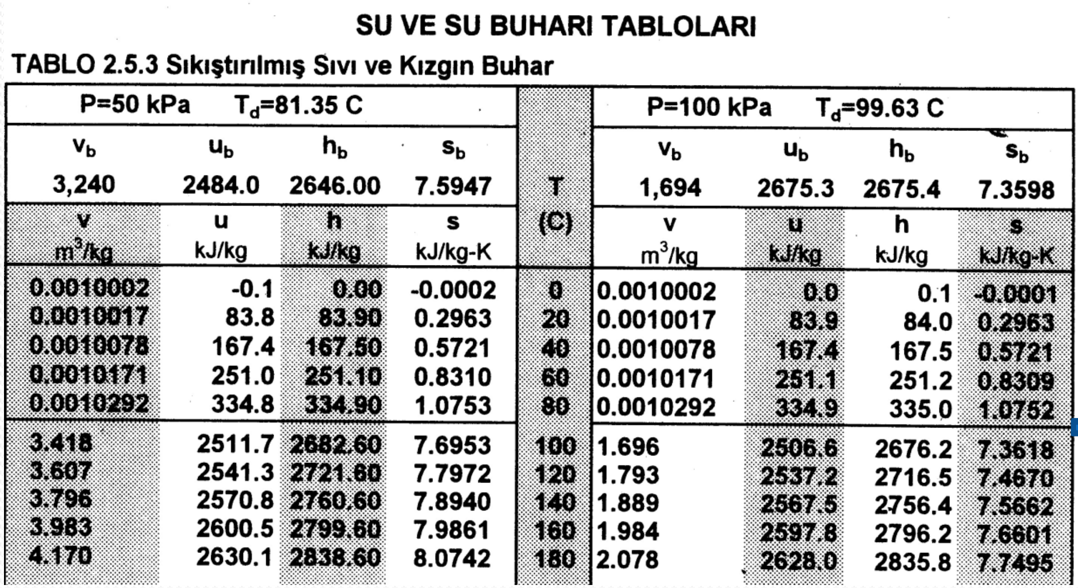
In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor.

In this region, temperature and pressure are independent properties.

Compared to saturated vapor, superheated vapor is characterized by

Lower pressures ($P < P_{sat}$ at a given T)
Higher tempreatures ($T > T_{sat}$ 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)

Table 2.5.3 also gives the properties of the compressed liquid in addition to superheated vapor.



SU VE SU BUHARI TABLOLARI

TABLO 2.5.3 Sıkıştırılmış Sıvı ve Kızgın Buhar

P=50 kPa T_d=81.35 C					P=100 kPa T_d=99.63 C			
v_b	u_b	h_b	s_b		v_b	u_b	h_b	s_b
3,240	2484.0	2646.00	7.5947	T	1,694	2675.3	2675.4	7.3598
v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	(C)	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg-K
0.0010002	-0.1	0.00	-0.0002	0	0.0010002	0.0	0.1	-0.0001
0.0010017	83.8	83.90	0.2963	20	0.0010017	83.9	84.0	0.2963
0.0010078	167.4	167.50	0.5721	40	0.0010078	167.4	167.5	0.5721
0.0010171	251.0	251.10	0.8310	60	0.0010171	251.1	251.2	0.8309
0.0010292	334.8	334.90	1.0753	80	0.0010292	334.9	335.0	1.0752
3.418	2511.7	2682.60	7.6953	100	1.696	2506.6	2676.2	7.3618
3.607	2541.3	2721.60	7.7972	120	1.793	2537.2	2716.5	7.4670
3.796	2570.8	2760.60	7.8940	140	1.889	2567.5	2756.4	7.5662
3.983	2600.5	2799.60	7.9861	160	1.984	2597.8	2796.2	7.6601
4.170	2630.1	2838.60	8.0742	180	2.078	2628.0	2835.8	7.7495

A partial listing of Table 2.5.3.

Above the line, the properties are given for the compressed liquid or subcooled region

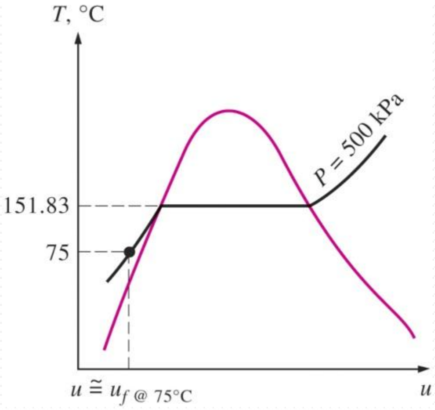
Below the line, the properties are given for the superheated region

Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure. Therefore, a compressed liquid may be approximated as a saturated liquid at the given temperature.

Given: P and T

$$v \cong v_{f\,@T}$$
$$u \cong u_{f\,@T}$$
$$h \cong h_{f\,@T}$$



Compressed liquid is characterized by

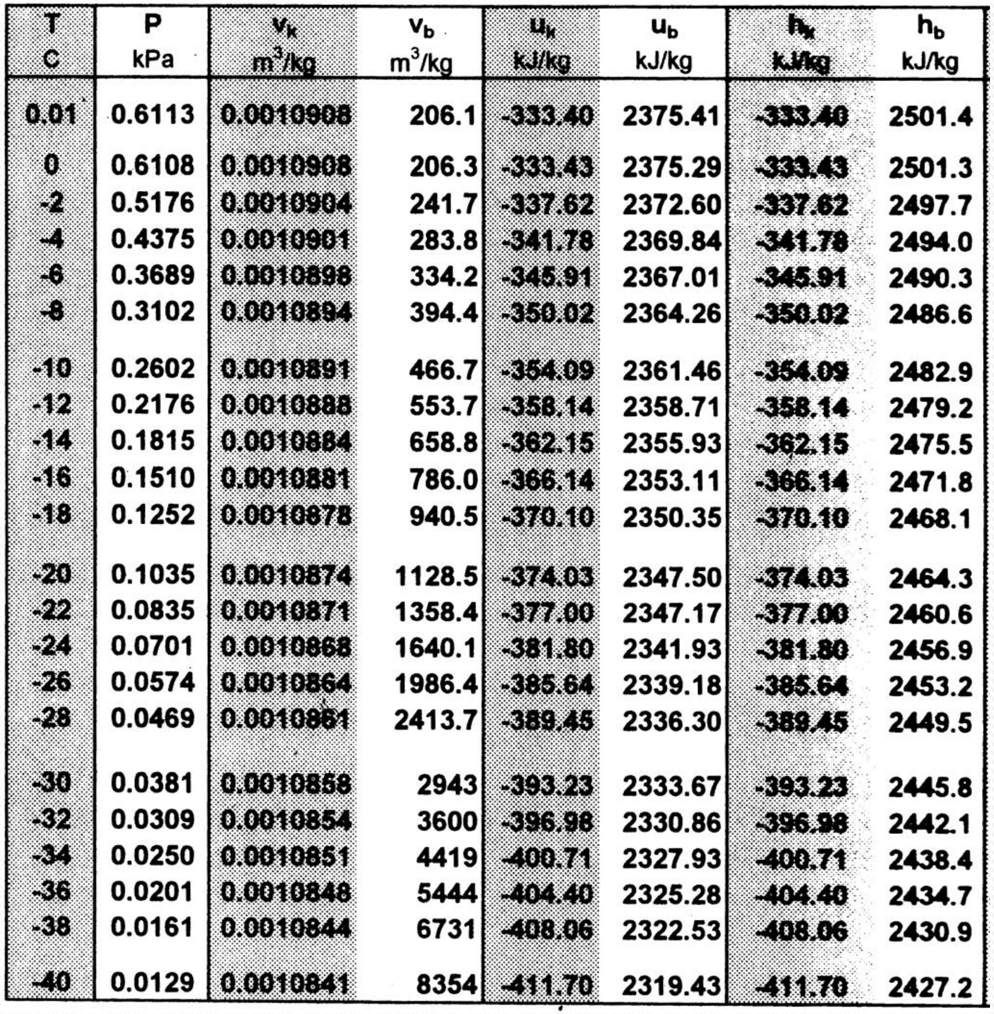
Higher pressures ($P > P_{sat}$ at a given T)
Lower tempreatures ($T < T_{sat}$ at a given P)
Lower specific volumes ($v < v_f$ at a given P or T)
Lower internal energies ($u < u_f$ at a given P or T)
Lower enthalpies ($h < h_f$ at a given P or T)

To demonstrate the use, the specific volume is 0.001 0437 m^3/kg at saturated-liquid water at 100°C and Mpa.

Suppose the pressure is increased to 10 MPa while the temperature is held constant at 100°C by the necessary transfer of heat. Table 2.5.1 gives this specific volume as 0.001 0386 m^3/kg. This is only a slight decrease since water is slightly compressible, and only a small error would be made if one assumed that the volume of a compressed liquid is equal to the specific volume of the saturated liquid at the same temperature.

Saturated solid and saturated vapor

TABLO 2.5.4 Doymuş Katı ve Doymuş Buhar

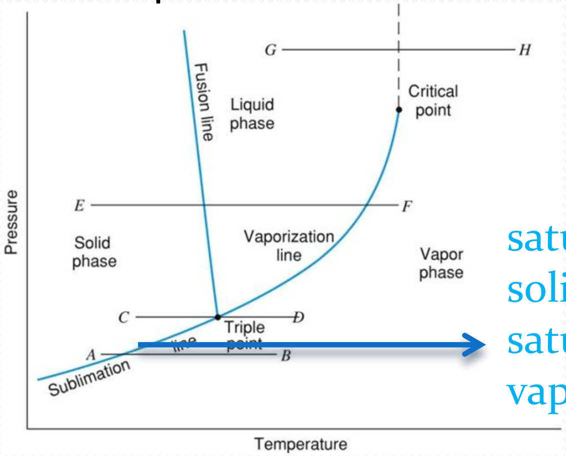


T C	P kPa	v_k m³/kg	v_b m³/kg	u_k kJ/kg	u_b kJ/kg	h_k kJ/kg	h_b kJ/kg
0.01	0.6113	0.0010908	206.1	-333.40	2375.41	-333.40	2501.4
0	0.6108	0.0010908	206.3	-333.43	2375.29	-333.43	2501.3
-2	0.5176	0.0010904	241.7	-337.62	2372.60	-337.62	2497.7
-4	0.4375	0.0010901	283.8	-341.78	2369.84	-341.78	2494.0
-6	0.3689	0.0010898	334.2	-345.91	2367.01	-345.91	2490.3
-8	0.3102	0.0010894	394.4	-350.02	2364.26	-350.02	2486.6
-10	0.2602	0.0010891	466.7	-354.09	2361.46	-354.09	2482.9
-12	0.2176	0.0010888	553.7	-358.14	2358.71	-358.14	2479.2
-14	0.1815	0.0010884	658.8	-362.15	2355.93	-362.15	2475.5
-16	0.1510	0.0010881	786.0	-366.14	2353.11	-366.14	2471.8
-18	0.1252	0.0010878	940.5	-370.10	2350.35	-370.10	2468.1
-20	0.1035	0.0010874	1128.5	-374.03	2347.50	-374.03	2464.3
-22	0.0835	0.0010871	1358.4	-377.00	2347.17	-377.00	2460.6
-24	0.0701	0.0010868	1640.1	-381.80	2341.93	-381.80	2456.9
-26	0.0574	0.0010864	1986.4	-385.64	2339.18	-385.64	2453.2
-28	0.0469	0.0010861	2413.7	-389.45	2336.30	-389.45	2449.5
-30	0.0381	0.0010858	2943	-393.23	2333.67	-393.23	2445.8
-32	0.0309	0.0010854	3600	-396.98	2330.86	-396.98	2442.1
-34	0.0250	0.0010851	4419	-400.71	2327.93	-400.71	2438.4
-36	0.0201	0.0010848	5444	-404.40	2325.28	-404.40	2434.7
-38	0.0161	0.0010844	6731	-408.06	2322.53	-408.06	2430.9
-40	0.0129	0.0010841	8354	-411.70	2319.43	-411.70	2427.2

Table 2.5.4 of the steam tables gives the properties of saturated solid and saturated vapor that are in equilibrium. The first column gives the temperature, and the second column gives the corresponding saturation pressure.

As would be expected, all these pressures are less than the triple-point pressure.

The next two columns give the specific volume of the saturated solid and saturated vapor.



saturated solid and saturated vapor

Other Property Tables

Property tables also includes thermodynamic tables for several other substances; refrigerant fluids ammonia, R-12, and R-134a and the cryogenic fluids nitrogen and methane.

Determine the phase for each of the following water states using tables and indicate the relative position in the *P-v*, *T-v*, and *P-T* diagrams.

a) 120°C, 500 kPa

b) 120°C, 0.5 m³/kg

Enter Table 2.5.1 with 120°C. The saturation pressure is 198.54 kPa, so we have a compressed liquid, point *a* in Figure 500 kPa>198 kPa

That is above the saturation line for 120°C. We could also have entered Table 2.5.2 with 500 kPa and found the saturation temperature as 151.84°C, so we would say it is subcooled liquid. 120°C<151.84 °C

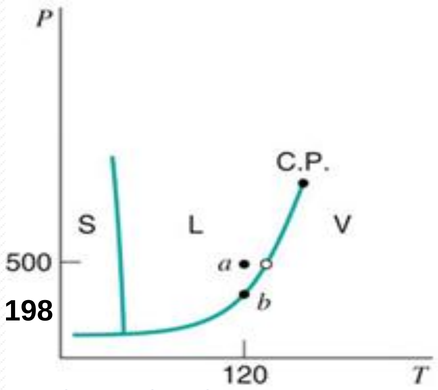
Higher pressures ($P > P_{sat}$ at a given T)

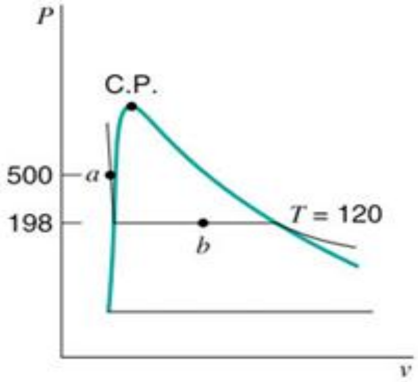
Lower tempreatures ($T < T_{sat}$ at a given P)

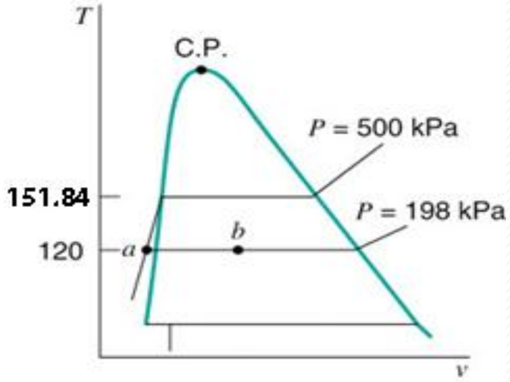
Lower specific volumes ($v < v_f$ at a given P or T)

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

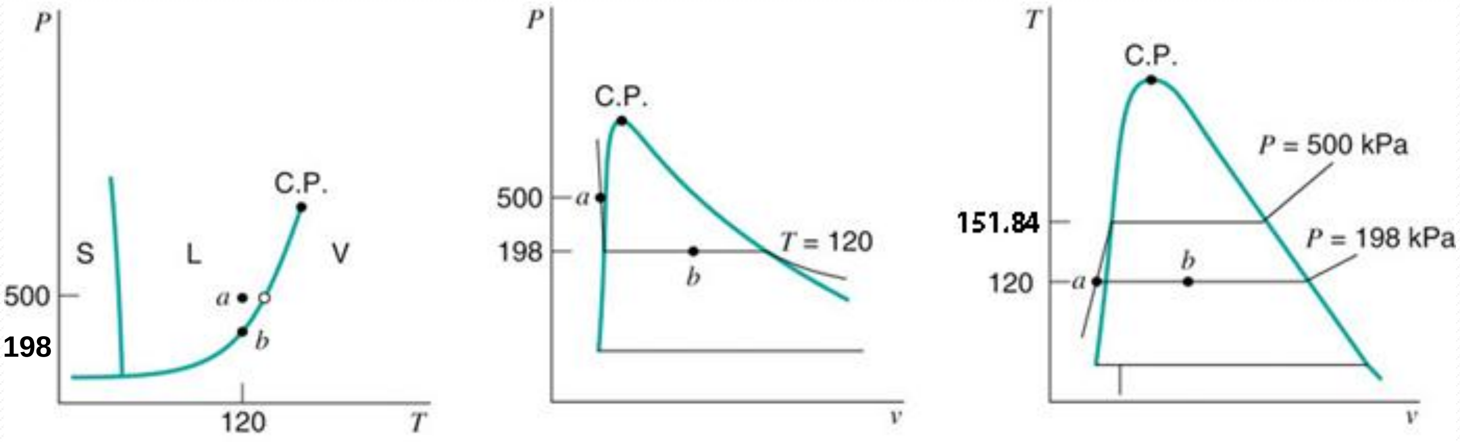
Lower enthalpies ($h < h_f$ at a given P or T)







Enter Table 2.5.1 with 120°C and notice that given specific volume between saturated liquid and vapor $v_f = 0.0010606 < v < v_g = 0.8915\ \mathrm{m^3/kg}$ so the state is a two phase mixture of liquid and vapor, point *b* in Figure. The state is to the left of the saturated vapor state and to the right of the saturated liquid state both seen in the *T*-*v* diagram.

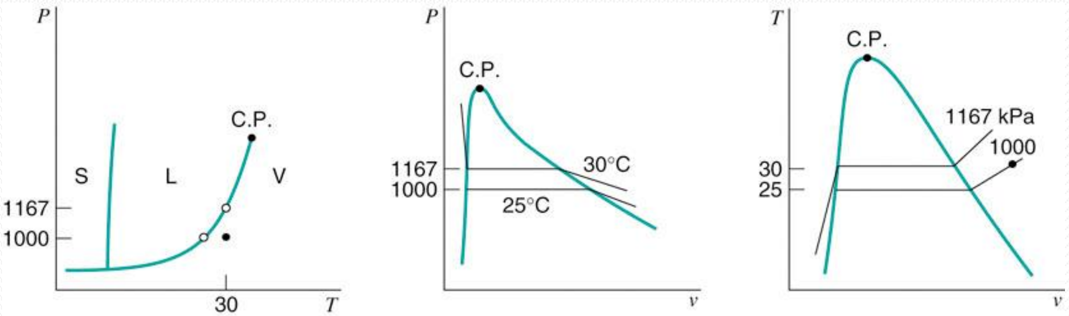


Determine the phase for each of the following states using the property tables and indicate the relative position in the *P-v*, *T-v* and *P-T* diagrams.

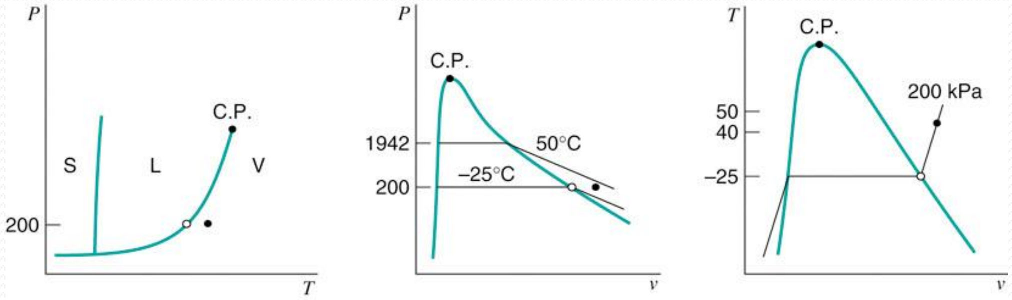
a. Ammonia 30°C, 1000 kPa

b. R-12 200 kPa, 0.15 m^3/kg

a. Enter Table 2.8.1 with 30°C. The saturation pressure is 1166.5 kPa. As we have lower P than saturated pressure (1166.49 kPa) at a given temperature, it is a superheated vapor state.



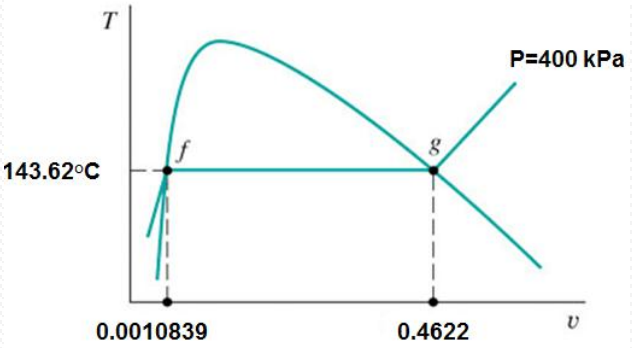
b. Enter Table 2.7.2 with 200 kPa and notice
$v = 0.15 > v_g = 0.08401$ m^3/kg
so from the *P-v* diagram the state is superheated vapor. We can find the state in Table 2.7.3 between 160 and 170°C.



Determine the temperature and quality (if defined) for water at a pressure of 400 kPa and at each of these specific volumes:

a. 0.4 m^3/kg

b. 0.7 m^3/kg



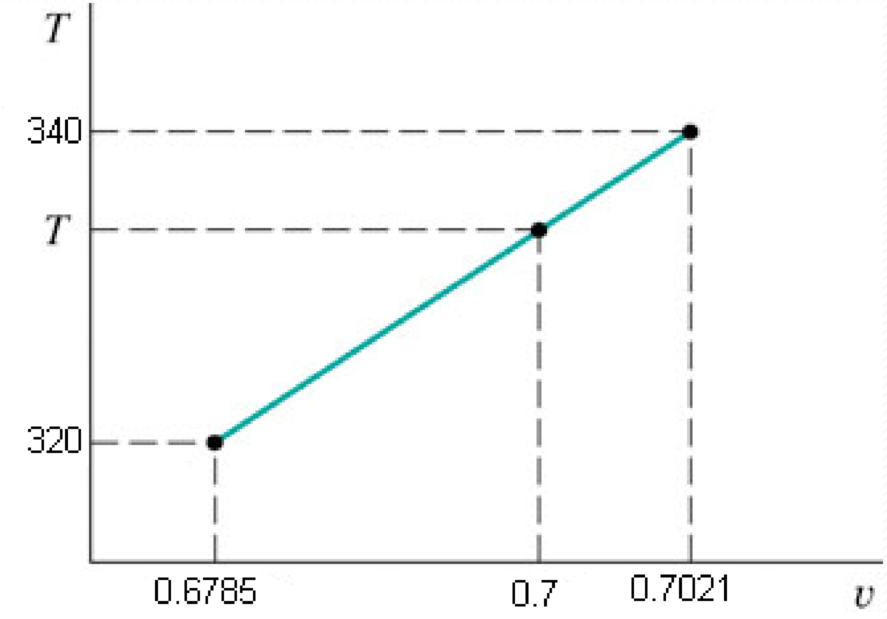
a. By comparison with the values in Figure, the state at which *v* is 0.4 m^3/kg is seen to be in the liquid-vapor two-phase region, at which *T* = 143.62°C, and the quality *x* is found from Eq. as

$$0.4 = 0.0010839 + x(0.4622 - 0.0010839) \qquad x = 0.865$$

Note that if we did not have Table 5.1.2 (as would be the case with the other substances listed tables), we could have interpolated in Table 5.1.1 between the 142°C and 144°C entries to get the v_f and v_g values for 400 kPa (143.62 °C).

b.By comparison with the values in Figure, the state at which *v* is 0.7 m^3/kg is seen to be in the superheated vapor region, in which quality is undefined, and the temperature for which, is found from Table 2.5.3.

In this case, *T is* found by linear interpolation between the 400 kPa specific-volume values at 320°C and 340°C, as shown in Fig. 3.14. This is an approximation for *T,* since the actual relation along the 400 kPa constant-pressure line is not exactly linear.



From the figure we have

$$slope = \frac{T - 320}{0.7 - 0.6785} = \frac{340 - 320}{0.7021 - 0.6785}$$

solving this gives T = 338.2°C.

A closed vessel contains 0.1 m^3 of saturated liquid and 0.9 m^3 of saturated vapor R-134a in equilibrium at 30°C. Determine the percent vapor on a mass basis.

Values of the saturation properties for R-134a are found from Table 2.6.1. The mass-volume relations then give

$$V_{liq} = m_{liq} v_f \qquad m_{liq} = 0.1/0.000843 = 118.6\,kg$$

$$V_{vap} = m_{vap} v_g \qquad m_{vap} = 0.9/0.02671 = 33.7\,kg$$

m = 152.3 kg = 118.6+33.7

$$x = \frac{m_{vap}}{m} = 0.221$$

That is, the vessel contains 90 % vapor by volume but only 23.4 % vapor by mass.

A rigid vessel contains saturated ammonia vapor at 20°C. Heat is transferred to the system until the temperature reaches 40°C. What is the final pressure?

Since the volume and mass does not change during this process, the specific volume also remains constant. From the ammonia tables, Table 2.8.1, we have

$$V_1 = V_2 = 0.1494 \text{ m}^3/\text{kg} \quad v_g \text{ at } 20°\text{C}$$

Since v_g *(0.0833* m³/kg*)* at 40°C is less than 0.1494 m³/kg, it is evident that in the final state the ammonia is superheated vapor. By interpolating between the 800 and 1000 kPa columns of Table 2.8.2, we find that

$P = 944.9$ kPa

v_g= *0.1773 at 800 kPa and* T = 40°C

v_g= *0.1388 at 1000 kPa and* T = 40°C

v_g= *0.1494 at ??? kPa and* T = 40°C

Determine the missing property of *P-v-T and x* if applicable for the following states
a. Nitrogen: -53.2°C, 400 kPa
b. Nitrogen: 100 K, 0.008 m³/kg

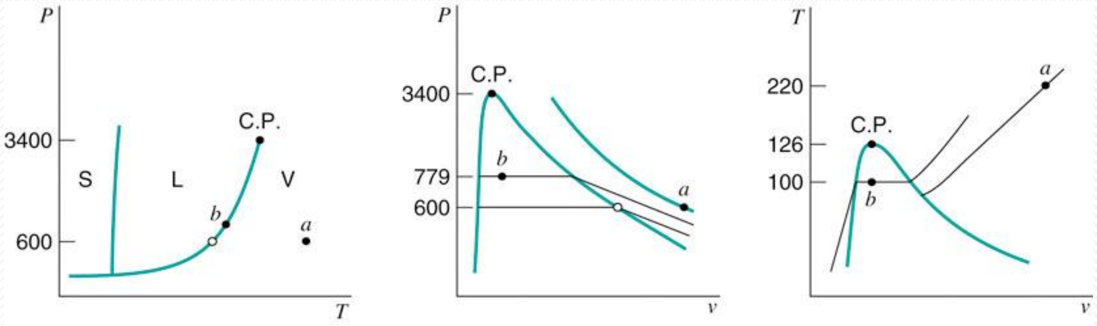
For nitrogen the properties are listed in Table 2.9 with temperature in Kelvin.

a. Enter in Table 2.9.1 with T = 273.2 - 53.2 = 220 K, which is higher than the critical T in the last entry.

Then proceed to the superheated vapor tables. We would also have realized this by looking at the critical properties in Table 2.1. From Table 2.9.2 in the subsection for 400 kPa (T_{sat} = 91.22 K) & 220 K v = 0.162290 m³/kg

b. Enter in Table 2.9.1 with T = 100 K and comparing v, we see that we have a two-phase state with a pressure as the saturation pressure, shown as b in Figure $P = P_{sat}$ = 779 kPa and the quality is

$$x = \frac{0.008 - 0.0001452}{0.031313 - 0.0001452} = 0.2201$$



Determine the pressure for water at 200°C with v = 0.4 m^3/kg.

Start in Table 2.5.1 with 200°C and note that $v > v_g = 0.1272\ m^3/kg$ so we have superheated vapor. Proceed to Table 2.5.3 at any subsection with 200°C; say we start at 200 kPa. There the $v = 1.0804$, which is too large so the pressure must be higher. For 400 kPa, $v = 0.5343$, and for 600 kPa, $v = 0.3520$

At 200°C and 200 kPa $v_g = 1.0804\ m^3/kg$

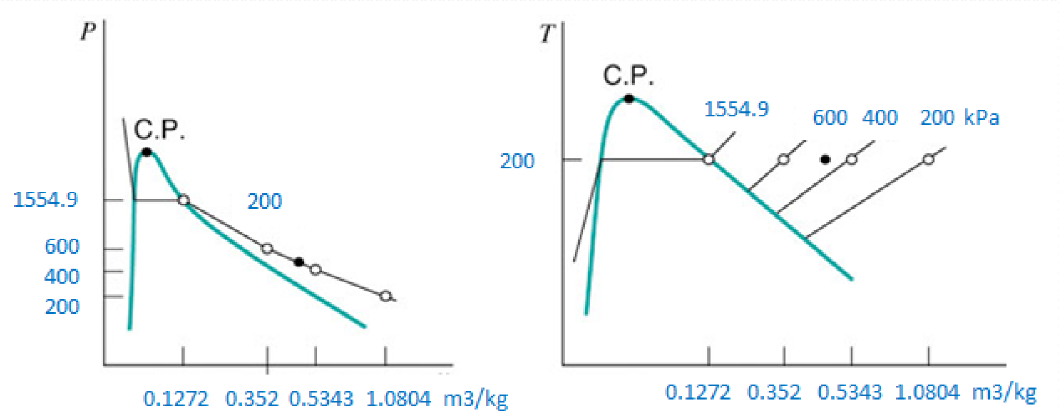
At 200°C and 400 kPa $v_g = 0.5343\ m^3/kg$

At 200°C and 600 kPa $v_g = 0.3520\ m^3/kg$

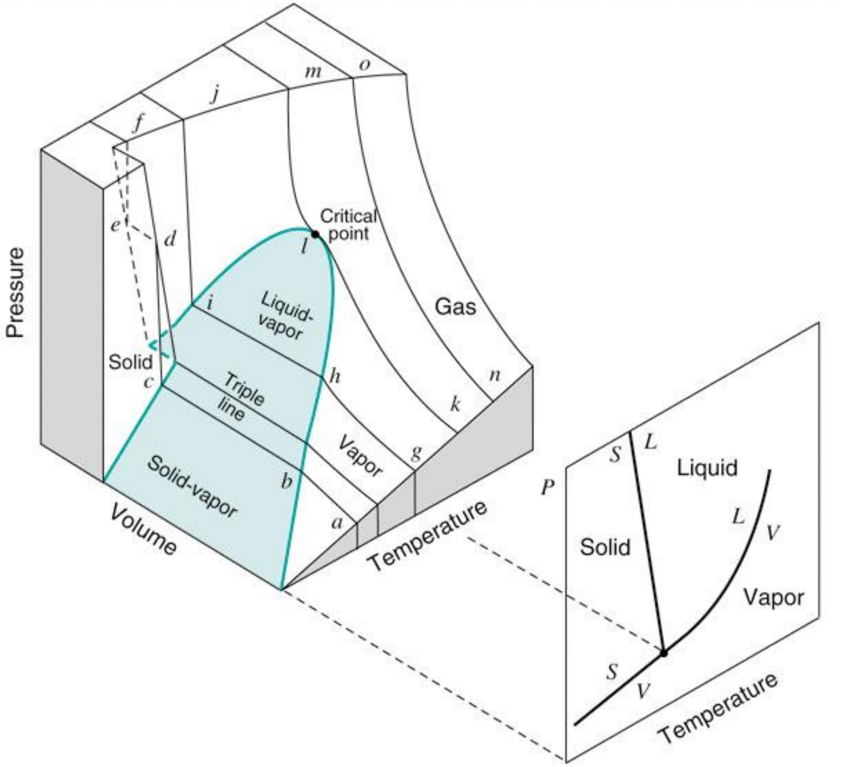
$\Big\}$ v = 0.4 m^3/kg.

A linear interpolation, Figure, between the two pressures is done to get P at the desired v.

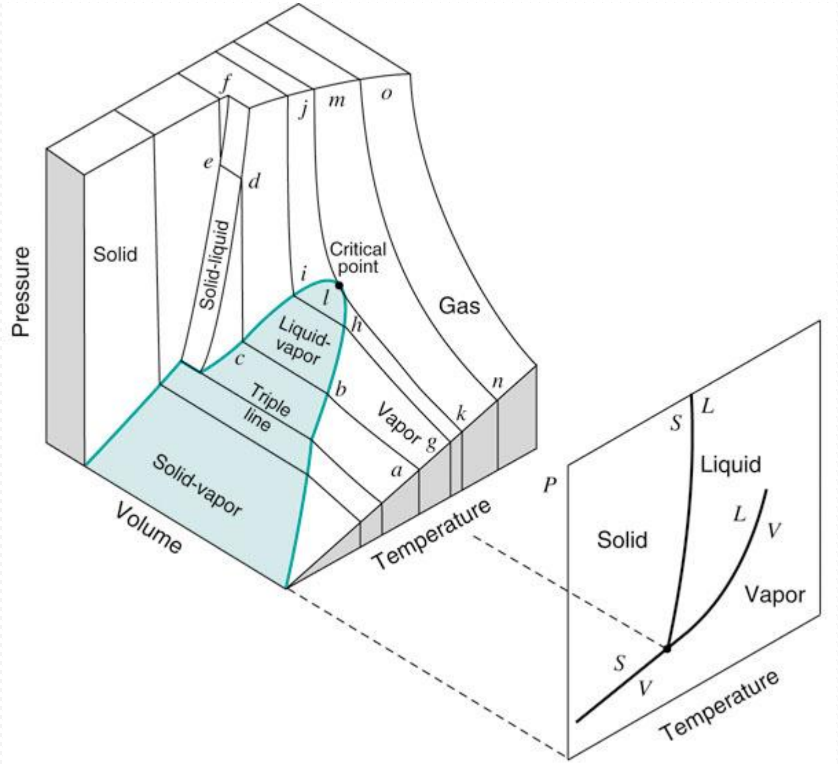
$$P = 400 + (600 - 400) * \frac{(0.4-0.5343)}{(0.352-0.5343)} = 547.34 \text{ kPa}$$



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.



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



P-*v*-*T* surface of a substance that *contracts* on freezing.

The P–V–T Behavior of Low– and Moderate– Density Gases

Equation of state: Any equation that relates the pressure, temperature, and specific volume of a substance.

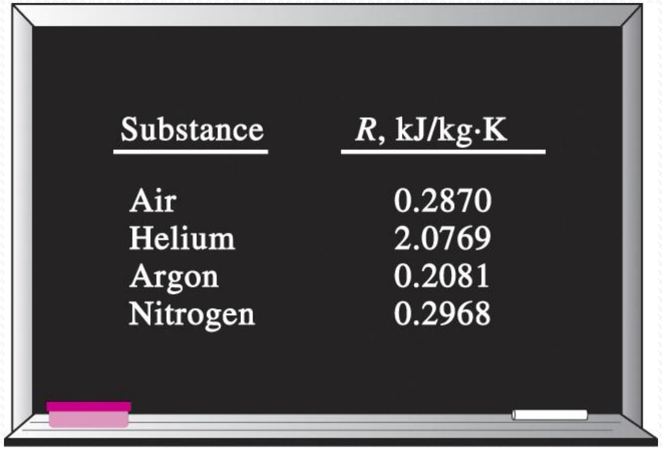
The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.

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

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

R: gas constant
M: molar mass (kg/kmol)
R_u: universal gas constant

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



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

Different substances have different gas constants.

Various expressions of ideal gas equation

$$V = mv \longrightarrow PV = mRT$$

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

$$V = N\bar{v} \longrightarrow P\bar{v} = R_uT$$

P = **absolute pressure** in MPa, or kPa
$\bar{v}$ = molar specific volume in m^3/kmol
T = **absolute temperature** in K
R_u = 8.314 kJ/(kmol·K)

Ideal gas equation at two states for a fixed mass
(Control Mass or Closed System)

Useful Ideal Gas Relation: The Combined Gas Law

By writing the ideal gas equation twice for a fixed mass and simplifying, the properties of an ideal gas at two different states are related by

$$m_1 = m_2$$

or

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

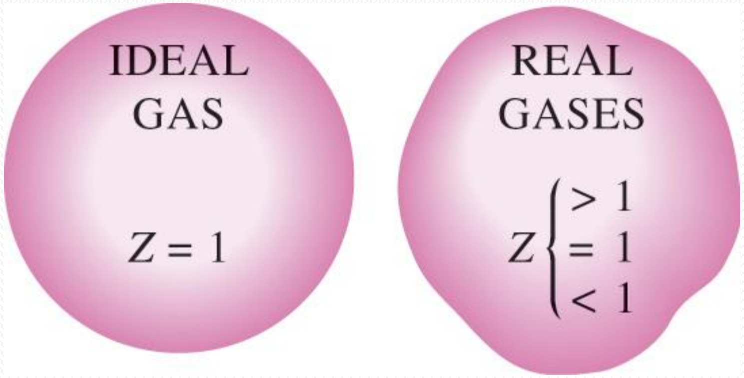
and eliminating gas constant

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

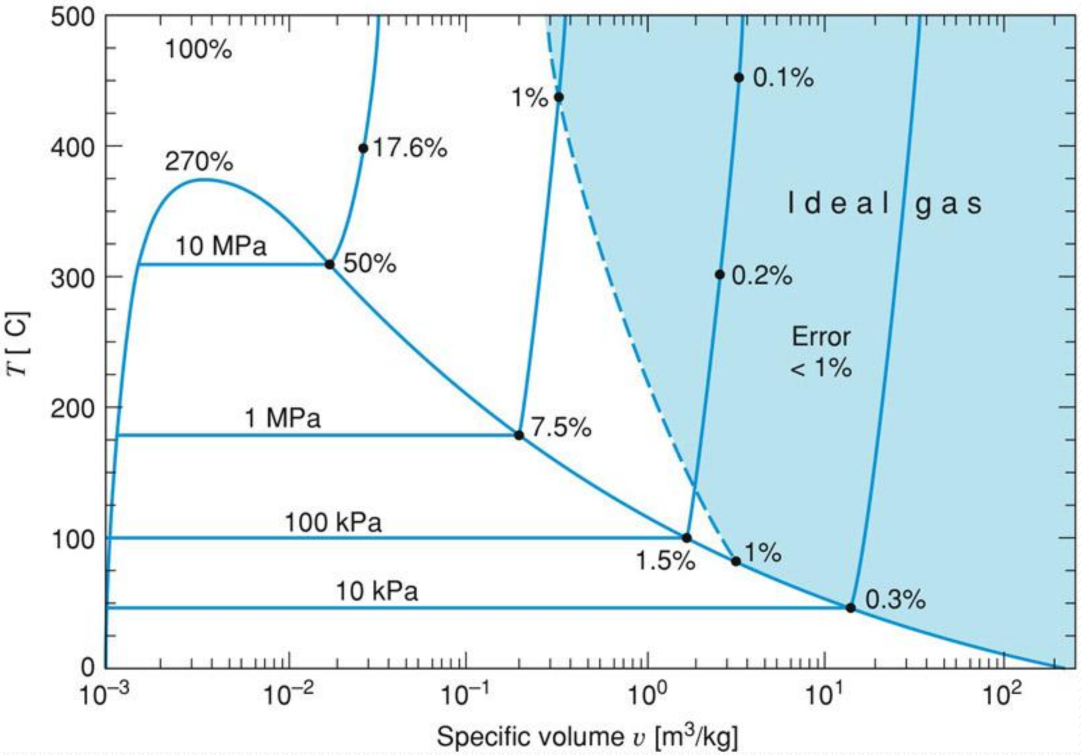
COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility factor *Z* A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT \qquad Z = \frac{Pv}{RT} \qquad Z = \frac{v_{\text{actual}}}{v_{\text{ideal}}}$$



The compressibility factor is unity for ideal gases.


500
400
300
200
100
0
100%
270%
17.6%
10 MPa
50%
1%
0.1%
Ideal gas
0.2%
Error
< 1%
1 MPa
7.5%
100 kPa
1.5%
1%
10 kPa
0.3%
T [C]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Specific volume v [m³/kg]

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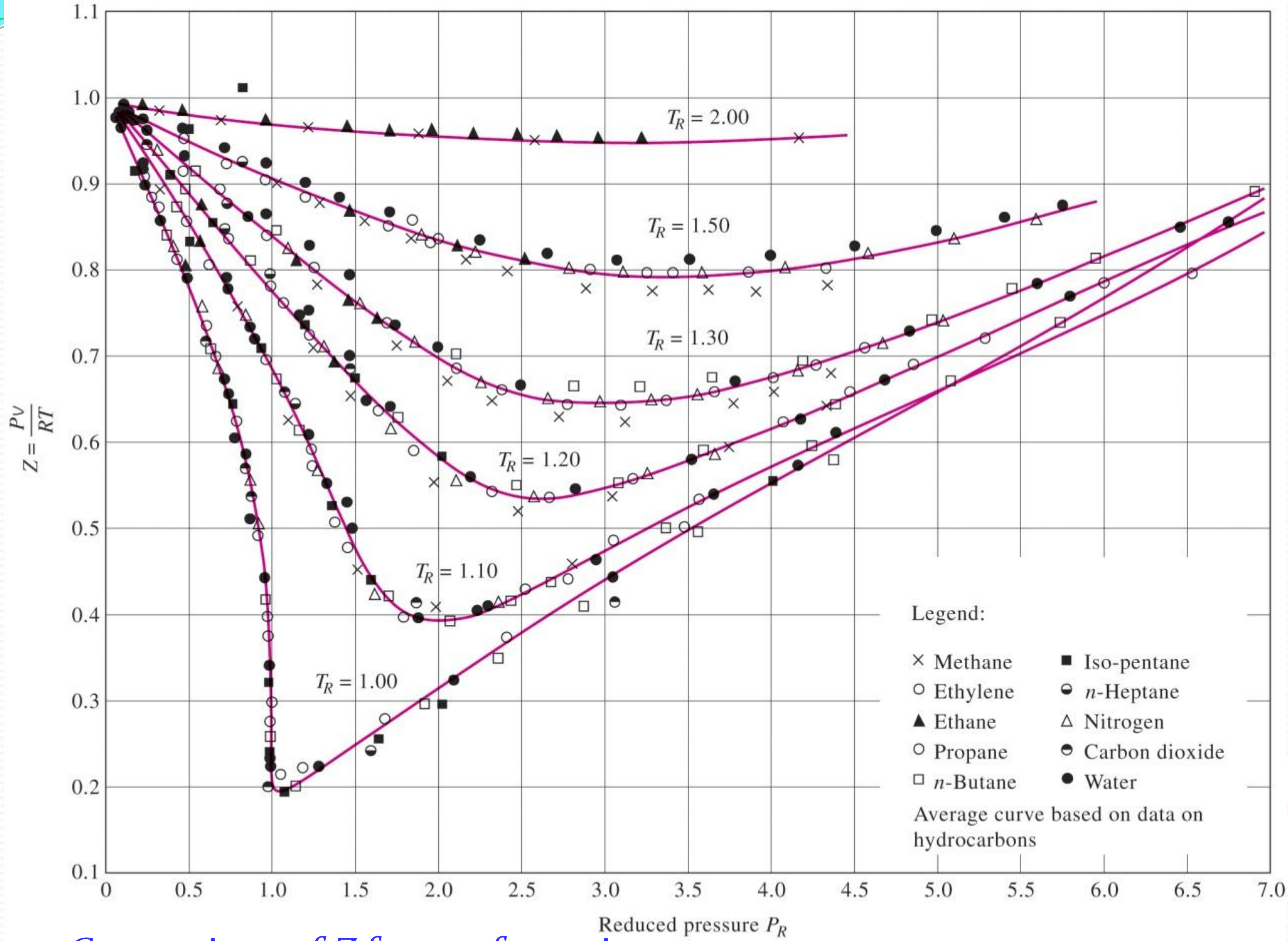


Comparison of *Z* factors for various gases.

Reduced pressure

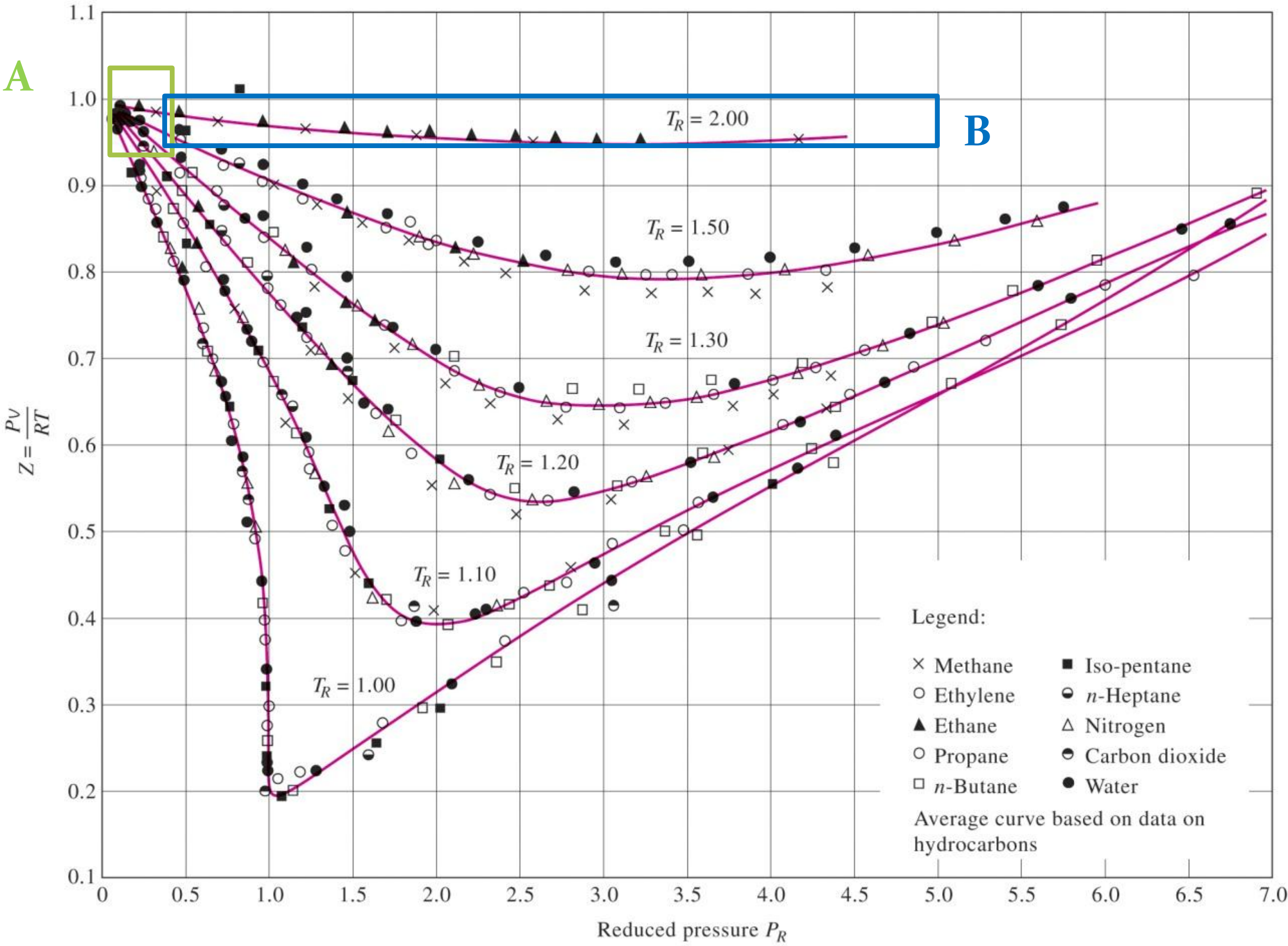
$$P_R = \frac{P}{P_{cr}}$$

Reduced temperature

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

Pseudo-reduced specific volume

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$



Ideal Gas Assumption
Region of Z~1

A) if the pressure is very low (that is, $P \ll P_c$), the ideal-gas model can be assumed with good accuracy, regardless of the temperature

B) at high temperatures (that is, greater than about $T \gtrsim 2T_c$) pressures as high as four or five times $P \lesssim 4-5P_c$

OTHER EQUATIONS OF STATE

Many such equations have been proposed and used to correlate the observed behavior of gases. As an example, the class of relatively simple equation known as cubic equations of state

van der Waals
Berthelet
Redlich-Kwang
Beattie-Bridgeman
Benedict-Webb-Rubin
Strobridge
Virial

Equation of state accurately represents the *P*-*v*-*T* behavior for a particular gas over the entire superheated vapor region

As an example, the class of relatively simple equation known as cubic equations of state

$$P = \frac{RT}{v-b} = \frac{a}{v^2 + cbv + db^2}$$