Borgnakke Sonntag

Fundamentals of Thermodynamics

SOLUTION MANUAL
CHAPTER 2

8e

Updated June 2013

CONTENT CHAPTER 2

SUBSECTION	PROB NO.
Concept problems	1-15
Phase diagrams, triple and critical points	16-24
General tables	25-64
Ideal gas	65-84
Compressibility factor	85-97
Equations of state	98-106
Review problems	107-125
Linear interpolation	126-130
Computer tables	131-135

In-Text Concept Questions

2.a

If the pressure is smaller than the smallest P_{sat} at a given T, what is the phase?

Refer to the phase diagrams in Figures 2.4
and 2.5. For a lower P you are below the
vaporization curve (or the sublimation curve)
and that is the superheated vapor region. You
have the gas phase.
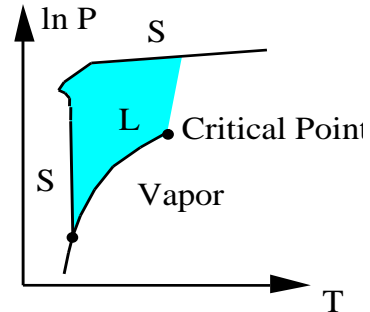
2.b

An external water tap has the valve activated by a long spindle so the closing
mechanism is located well inside the wall. Why is that?

Solution:
By having the spindle inside the wall the coldest location with water when the valve
is closed is kept at a temperature above the freezing point. If the valve spindle was
outside there would be some amount of water that could freeze while it is trapped
inside the pipe section potentially rupturing the pipe.

2.c

What is the lowest temperature (approximately) at which water can be liquid?

Look at the phase diagram in Fig. 2.4. At the border between ice I, ice III and the liquid region is a triple point which is the lowest T where you can have liquid. From the figure it is estimated to be about 255 K i.e. at -18°C.

T ≈ 255 K ≈ - 18°C
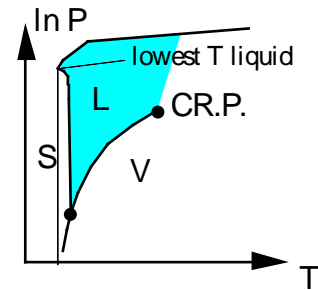
2.d

Some tools should be cleaned in water at a least 150°C. How high a P is needed?

Solution:

If I need liquid water at 150°C I must have a pressure that is at least the saturation pressure for this temperature.

Table B.1.1: 150°C, P_{sat} = 475.9 kPa.

2.e

Water at 200 kPa has a quality of 50%. Is the volume fraction $V_g/V_{tot} < 50\%$ or $> 50\%$?

This is a two-phase state at a given pressure and without looking in the table we know that v_f is much smaller than v_g.

From the definition of quality we get the masses from total mass, m, as

$$m_f = (1 - x)\, m, \qquad m_g = x\, m$$

The volumes are

$$V_f = m_f\, v_f = (1 - x)\, m\, v_f, \qquad V_g = m_g\, v_g = x\, m\, v_g$$

So when half the mass is liquid and the other half is vapor the liquid volume is much smaller that the vapor volume. The vapor volume is thus much more than 50% of the total volume. Only right at the critical point is $v_f = v_g$ for all other states $v_g > v_f$ and the difference is larger for smaller pressures.

2.f

Why are most of the compressed liquid or solid regions not included in the printed tables?

For the compressed liquid and the solid phases the specific volume and thus density is nearly constant. These surfaces are very steep nearly constant v and there is then no reason to fill up a table with the same value of v for different P and T.

2.g

Why is it not typical to find tables for Ar, He, Ne or air like an Appendix B table?

The temperature at which these substances are close to the two-phase region is very low. For technical applications with temperatures around atmospheric or higher they are ideal gases. Look in Table A.2 and we can see the critical temperatures as

Ar : 150.8 K   He: 5.19 K   Ne: 44.4 K

It requires a special refrigerator in a laboratory to bring a substance down to these cryogenic temperatures.

2.h

What is the percent change in volume as liquid water freezes? Mention some effects the volume change can have in nature and in our households.

The density of water in the different phases can be found in Tables A.3 and A.4 and in Table B.1.

From Table B.1.1 $v_f = 0.00100 \text{ m}^3/\text{kg}$

From Table B.1.5 $v_i = 0.0010908 \text{ m}^3/\text{kg}$

Percent change: $100 \dfrac{v_i - v_f}{v_f} = 100 \times \dfrac{0.0010908 - 0.001}{0.001} = 9.1 \text{ \% increase}$

Liquid water that seeps into cracks or other confined spaces and then freezes will expand and widen the cracks. This is what destroys any porous material exposed to the weather on buildings, roads and mountains. It can burst water pipes and crack engine blocks (that is why you put anti-freeze in it).

2.i

How accurate is it to assume that methane is an ideal gas at room conditions?

From Table A.2: $T_c = 190.4$ K, $P_c = 4.60$ MPa

So at room conditions we have much higher $T > T_c$ and $P << P_c$ so this is the ideal gas region. To confirm look in Table B.7.2

$$100 \text{ kPa, } 300 \text{ K,}\quad v = 1.55215 \text{ m}^3/\text{kg}$$

Find the compressibility factor (R from Table A.5) as

$$Z = Pv/RT = \frac{100 \text{ kPa} \times 1.55215 \text{ m}^3/\text{kg}}{0.5183 \text{ kJ/kg-K} \times 300 \text{ K}} = 0.99823$$

so Z is 1 with an accuracy of 0.2% better than most measurements can be done.

2.j

I want to determine a state of some substance, and I know that P = 200 kPa; is it helpful to write PV = mRT to find the second property?

NO. You need a second property.

Notice that two properties are needed to determine a state. The EOS can give you a third property if you know two, like (P,T) gives v just as you would get by entering a table with a set (P,T). This EOS substitutes for a table when it is applicable.

2.k

A bottle at 298 K should have liquid propane; how high a pressure is needed? (use Fig. D.1)

To have a liquid the pressure must be higher than or equal to the saturation pressure. There is no printed propane table so we use the compressibility chart and Table A.2

Propane Table A.2: $T_c = 369.8$ K, $P_c = 4.25$ MPa

The reduced temperature is:

$$T_r = \frac{T}{T_c} = \frac{298}{369.8} = 0.806,$$

for which we find in Fig. D.1: $P_{r\ sat} = 0.25$

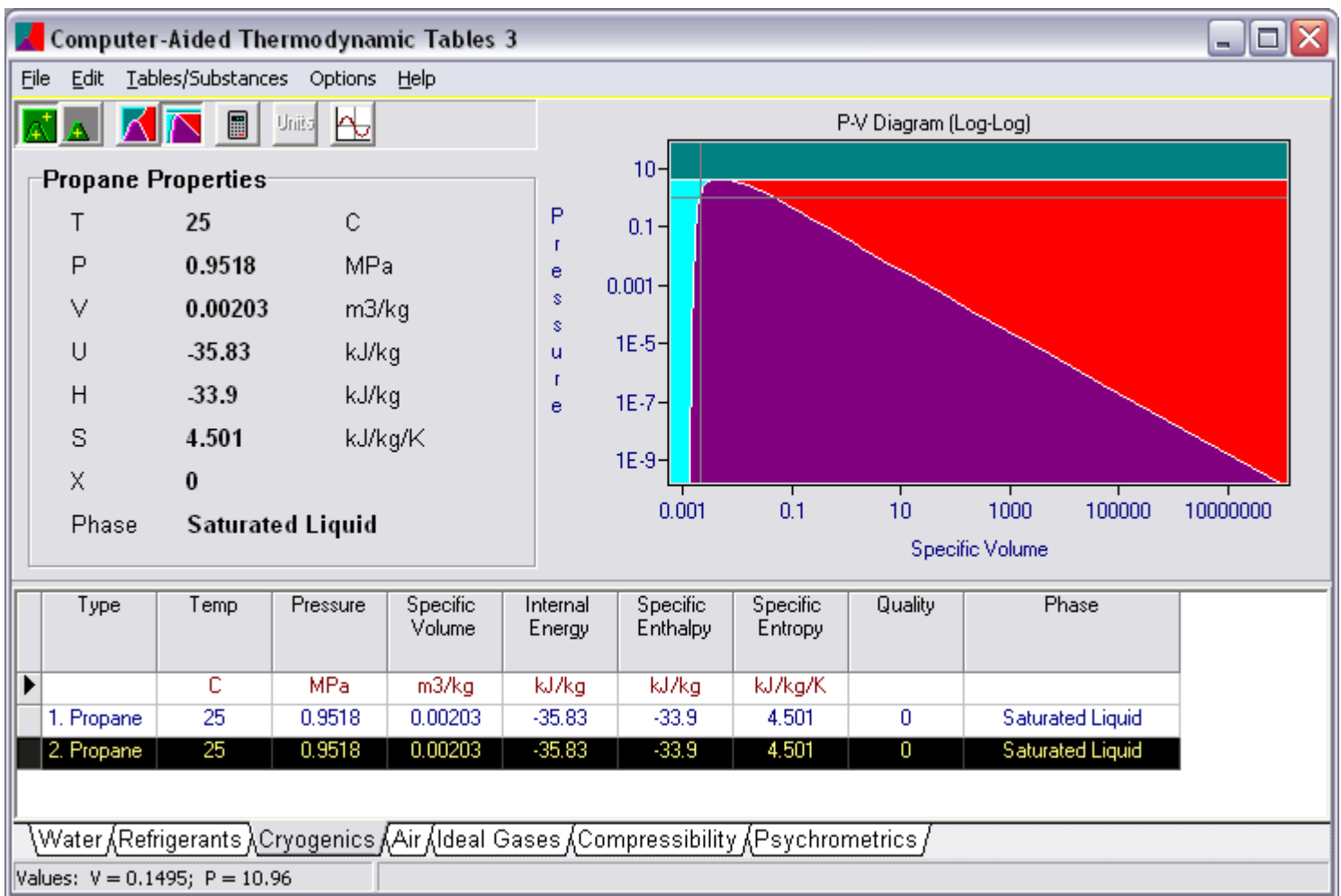$$P = P_{r\ sat}\ P_c = 0.25 \times 4.25 \text{ MPa} = \textbf{1.06 MPa}$$

2.1

A bottle at 298 K should have liquid propane; how high a pressure is needed? (use the software)

To have a liquid the pressure must be higher than or equal to the saturation pressure. There is no printed propane table but the software has propane included

Start CATT3, select cryogenic substances, propane

select calculator,   select case 4 (T, x) = (25°C, 0)

⇨   P = **0.9518 MPa**

Computer-Aided Thermodynamic Tables 3

File   Edit   Tables/Substances   Options   Help

P-V Diagram (Log-Log)

Propane Properties

T	25	C
P	**0.9518**	MPa
V	**0.00203**	m3/kg
U	**-35.83**	kJ/kg
H	**-33.9**	kJ/kg
S	**4.501**	kJ/kg/K
X	**0**	
Phase	**Saturated Liquid**	

Type	Temp	Pressure	Specific Volume	Internal Energy	Specific Enthalpy	Specific Entropy	Quality	Phase
	C	MPa	m3/kg	kJ/kg	kJ/kg	kJ/kg/K		
1. Propane	25	0.9518	0.00203	-35.83	-33.9	4.501	0	Saturated Liquid
2. Propane	25	0.9518	0.00203	-35.83	-33.9	4.501	0	Saturated Liquid

\Water /Refrigerants \Cryogenics /Air /Ideal Gases /Compressibility /Psychrometrics /

Values: V = 0.1495; P = 10.96

Concept Problems

2.1

Are the pressures in the tables absolute or gauge pressures?

Solution:
The behavior of a pure substance depends on the absolute pressure, so P in the tables is absolute.

2.2

What is the minimum pressure for which I can have liquid carbon dioxide?

Look at the phase diagram in Fig. 2.5. The minimum P in the liquid phase is at the triple point. From Table 2.2 this is at **520 kPa** (a similar value around 4-500 kPa is seen in Fig. 2.5).

The 100 kPa is below the triple point.
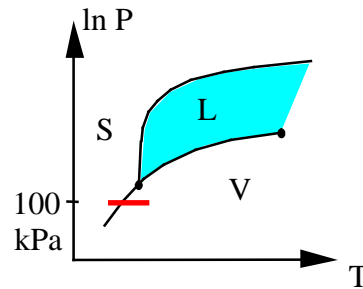
2.3

When you skate on ice, a thin liquid film forms under the skate. How can that be?

The ice is at some temperature below the freezing temperature for the atmospheric pressure of 100 kPa = 0.1 MPa and thus to the left of the fusion line in the solid ice I region of Fig. 2.4. As the skate comes over the ice the pressure is increased dramatically right under the blade so it brings the state straight up in the diagram crossing the fusion line and brings it into a liquid state at same temperature.

The very thin liquid film under the skate changes the friction to be viscous rather than a solid to solid contact friction. Friction is thus significantly reduced.

Comment: The latest research has shown that the pressure may not be enough to generate the liquid, but that such a liquid layer always exist on an ice surface, maybe only a few molecules thick (dependent upon temperature). At really low T say -40°C no such liquid layer exists which is why your finger can stick to such a surface.

2.4

   At a higher elevation like in mountains the pressure is lower, what effect does that have for cooking food?

   A lower pressure means that water will boil at a lower temperature, see the vaporization line in Fig. 2.4, or in Table B.1.2 showing the saturated temperature as a function of the pressure. You therefore must increase the cooking time a little.

2.5

Water at room temperature and room pressure has $v \approx 1 \times 10^n$ m^3/kg what is n?

        See Table B.1.1 or B.1.2 to determine it is in the liquid phase
        (you should know this already).
        Table A.4 or from B1.1 at 20°C: n = –3   (v = 0.00100 m^3/kg)

2.6

Can a vapor exist below the triple point temperature?

Look at the phase diagrams in Figs 2.4 and 2.5. Below the triple point the
sublimation curve has very small pressures, but not zero. So for pressures below the
saturation pressure the substance is a vapor. If the phase diagram is plotted in linear
coordinates the small vapor region is nearly not visible.

2.7

In Example 2.1 b is there any mass at the indicated specific volume? Explain.

This state is a two-phase mixture of liquid and vapor. There is no mass at the
indicated state, the v value is an average for all the mass, so there is some mass at the
saturated vapor state (fraction is the quality x) and the remainder of the mass is
saturated liquid (fraction 1-x).

2.8

Sketch two constant-pressure curves (500 kPa and 30 000 kPa) in a T-v diagram and indicate on the curves where in the water tables you see the properties.
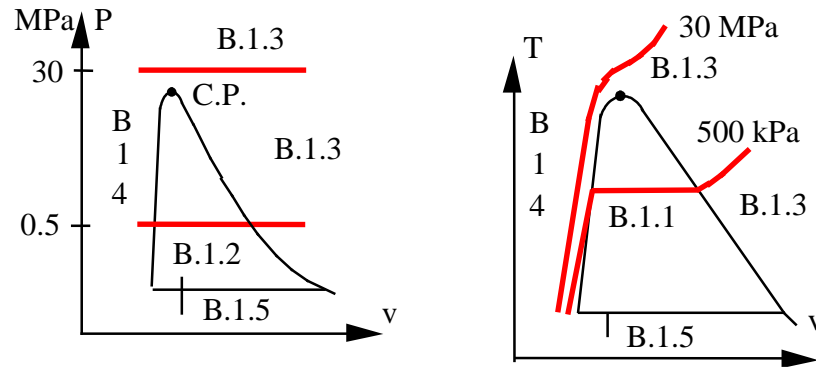
The 30 MPa line in Table B.1.4 starts at 0^oC and table ends at 380^oC, the line is continued in Table B.1.3 starting at 375^oC and table ends at 1300^oC.

The 500 kPa line in Table B.1.4 starts at 0.01^oC and table ends at the saturated liquid state (151.86^oC). The line is continued in Table B.1.3 starting at the saturated vapor state (151.86^oC) continuing up to 1300^oC.

2.9

If I have 1 L of R-410A at 1 MPa, 20°C how much mass is that?

R-410A Tables B.4:

B.4.1 P_{sat} = 1444.2 kPa at 20°C so superheated vapor.

B.4.2 v = 0.02838 m³/kg   under subheading 1000 kPa

$$m = \frac{V}{v} = \frac{0.001 \text{ m}^3}{0.02838 \text{ m}^3/\text{kg}} = \textbf{0.0352 kg} = \textbf{35.2 g}$$
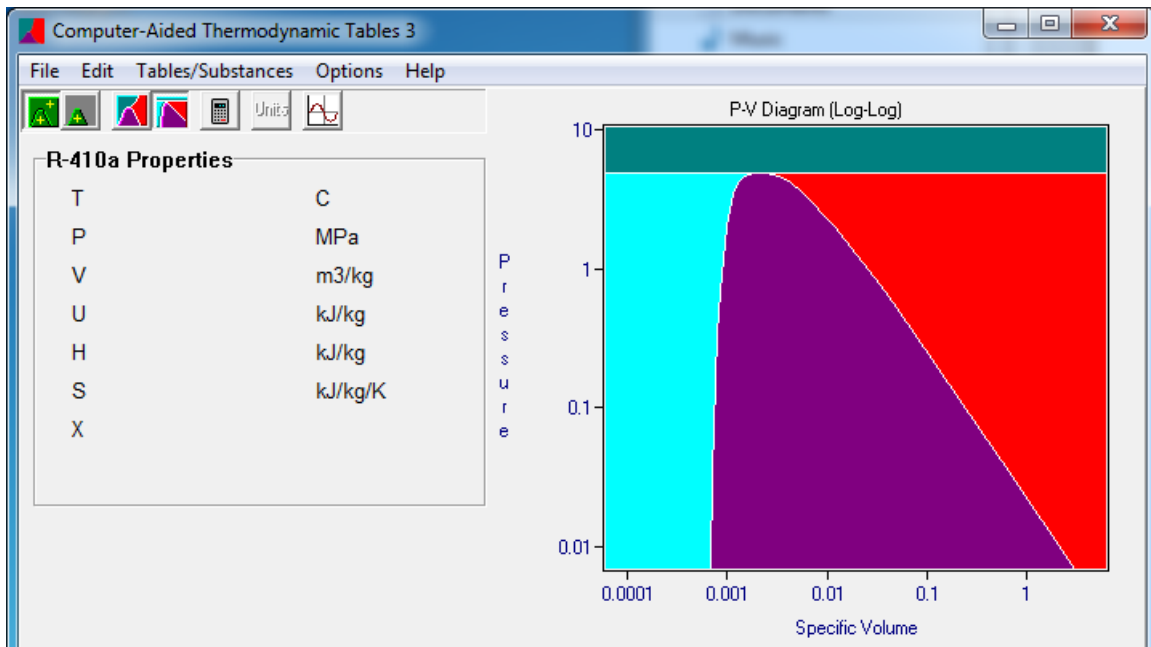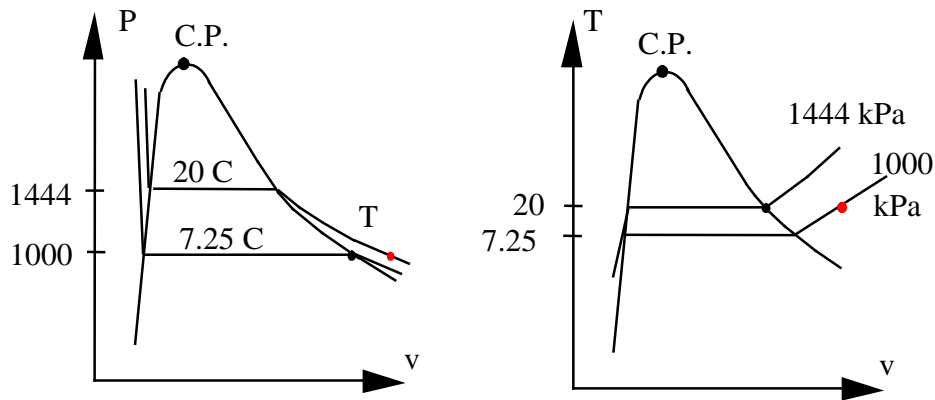
The P-v (log-log) diagram from CATT3, P in MPa and v in m³/kg.

2.10

Locate the state of ammonia at 200 kPa, -10°C. Indicate in both the P-v and the T-v
diagrams the location of the nearest states listed in the printed Table B.2

2.11

   Why are most of the compressed liquid or solid regions not included in the printed tables?

   For the compressed liquid and the solid phases the specific volume and thus density is nearly constant. These surfaces are very steep nearly constant v and there is then no reason to fill up a table with the same value of v for different P and T.

2.12

How does a constant v-process look like for an ideal gas in a P-T diagram?

For an ideal gas: Pv = RT so then   P = (R/v) T

Constant v is a straight line with slope (R/v) in the P-T diagram
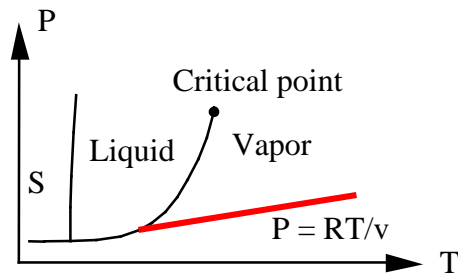
2.13

If $v = RT/P$ for an ideal gas what is the similar equation for a liquid?

The equation for a liquid is: $v = \text{Constant} = v_o$

If you include that v increases a little with T then: $v = v_o + C\,(T - T_o)$
where C is a small constant with units $m^3/kg\text{-}K$.

2.14

To solve for v given (P, T) in Eq.2.14 , what is the mathematical problem?

To solve for v in Eq. 2.14 multiply with the de-numerators so we get the form

$$P\, f_1(v) = RT\, f_2(v) - a\, (v - b)$$

This is a 3rd order polynomial (a cubic) function in v. The problem then is to find the roots or zero points in this cubic equation. The mathematical subject to study is to find zero points of functions (or roots). Typically you will do it by some iteration technique. Successive substitutions, bi-section, Newton-Raphson are some of the methods you should learn.

2.15

As the pressure of a gas becomes larger, Z becomes larger than 1. What does that imply?

$$Pv = Z\,RT$$

So for a given P, the specific volume v is then larger than predicted by the ideal gas law. The molecules are pressed so close together that they have repulsive forces between them (the electron clouds are getting closer). The ideal gas law assumes the atoms (molecules) are point masses with no interactions between them and thus has a limit of zero specific volume as P goes to infinity. Real molecules occupy some volume and the outer shell has a number of electrons with negative charges which can interact with one another if they are close enough.

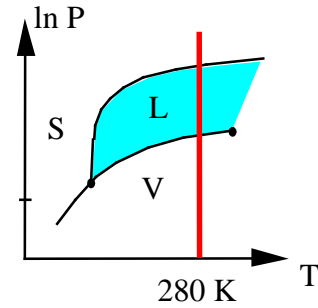**Phase Diagrams, Triple and Critical Points**

2.16

Carbon dioxide at 280 K can be in different phases. Indicate the pressure range you have for each of the three phases (vapor, liquid and solid).

Look at the P-T phase diagram in Fig. 2.5 at 280 K:

$P <$ 4000 kPa	vapor
4000 kPa $< P <$ 400 MPa	liquid
400 MPa $< P$	solid

2.17

Modern extraction techniques can be based on dissolving material in supercritical fluids such as carbon dioxide. How high are pressure and density of carbon dioxide when the pressure and temperature are around the critical point? Repeat for ethyl alcohol.

Solution:

CO_2 :

Table A.2: $P_c =$ **7.38 MPa**, $T_c = 304$ K, $v_c = 0.00212$ m^3/kg

$$\rho_c = 1/v_c = 1/0.00212 = \textbf{472 kg/m}^3$$

C_2H_5OH:

Table A.2: $P_c =$ **6.14 MPa**, $T_c = 514$ K, $v_c = 0.00363$ m^3/kg

$$\rho_c = 1/v_c = 1/0.00363 = \textbf{275 kg/m}^3$$

2.18

The ice cap on the North Pole could be 1000 m thick with a density of 920 kg/m^3.
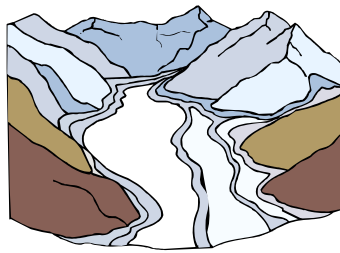Find the pressure at the bottom and the corresponding melting temperature.

Solution:

$$\rho_{ICE} = 920 \text{ kg/m}^3$$

$$\Delta P = \rho gH = 920 \text{ kg/m}^3 \times 9.80665 \text{ m/s}^2 \times 1000 \text{ m} = 9\ 022\ 118 \text{ Pa}$$

$$P = P_O + \Delta P = 101.325 + 9022 = \textbf{9123 kPa}$$

See figure 3.7 liquid solid interphase => $\mathbf{T_{LS} = -1°C}$
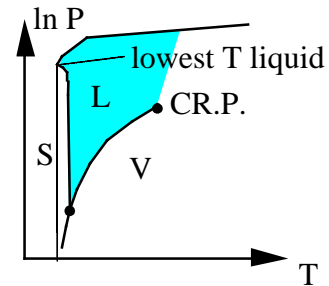
2.19

Find the lowest temperature at which it is possible to have water in the liquid phase. At what pressure must the liquid exist?

Solution:

There is no liquid at lower temperatures than on the fusion line, see Fig. 3.7, saturated ice III to liquid phase boundary is at

T ≈ 263K ≈ - 10°C and
P ≈ 210 MPa

2.20

Water at 27°C can exist in different phases dependent upon the pressure. Give the approximate pressure range in kPa for water being in each one of the three phases vapor, liquid or solid.
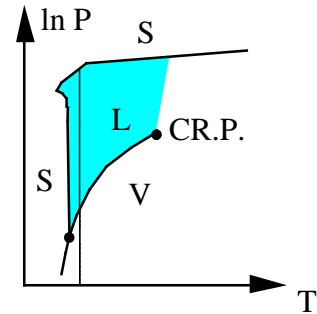
Solution:

The phases can be seen in Fig. 2.4, a sketch of which is shown to the right.

$T = 27\ °C = 300\ K$

From Fig. 2.4:

$P_{VL} \approx 4 \times 10^{-3}\ MPa = 4\ kPa,$

$P_{LS} = 10^3\ MPa$

$$0 < P < \quad 4\ kPa \qquad \textbf{VAPOR}$$
$$0.004\ MPa < P < 1000\ MPa \qquad \textbf{LIQUID}$$
$$P > 1000\ MPa \qquad \textbf{SOLID (ICE)}$$

2.21

Dry ice is the name of solid carbon dioxide. How cold must it be at atmospheric (100 kPa) pressure? If it is heated at 100 kPa what eventually happens?
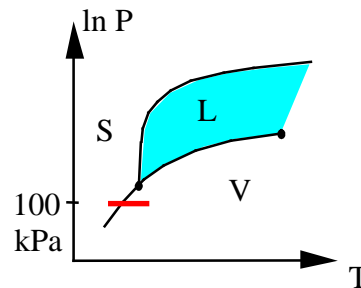
Solution:

The phase boundaries are shown in Figure 2.5
At 100 kPa the carbon dioxide is solid if   **T < 190 K**
It goes directly to a vapor state without becoming a liquid hence its name.

The 100 kPa is below
the triple point.

2.22

What is the lowest temperature in Kelvin for which you can see metal as a liquid if the metal is *a.* mercury   *b.* zinc

Solution:

Assume the two substances have a phase diagram similar to Fig. 2.5, then the triple point is the lowest T with liquid possible the data is from Table 2.1

$$T_a = -39^oC = \textbf{234 K}$$

$$T_b = 419^oC = \textbf{692 K}$$

2.23

A substance is at 2 MPa, 17°C in a rigid tank. Using only the critical properties can the phase of the mass be determined if the substance is oxygen, water or propane?

Solution:

Find state relative to critical point properties which are from Table A.2:

a) Oxygen O_2 : 5.04 MPa   154.6 K

b) Water H_2O : 22.12 MPa   647.3 K

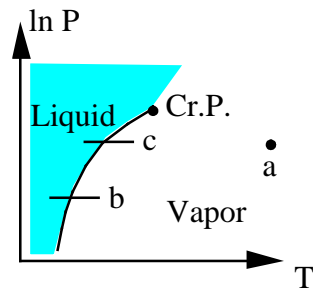c) Propane C_3H_8 : 4.25 MPa   369.8 K

State is at 17 °C = 290 K and   2 MPa $< P_c$

for all cases:

O_2 : T $\gg T_c$ Superheated vapor P < Pc

H_2O : T $\ll T_c$;   P $\ll P_c$

you cannot say.

C_3H_8 : T < T_c ; P < P_c you cannot say

2.24

Give the phase for the following states.

Solution:

a. CO_2 $T = 40°C$ $P = 0.5$ MPa   Table A.2
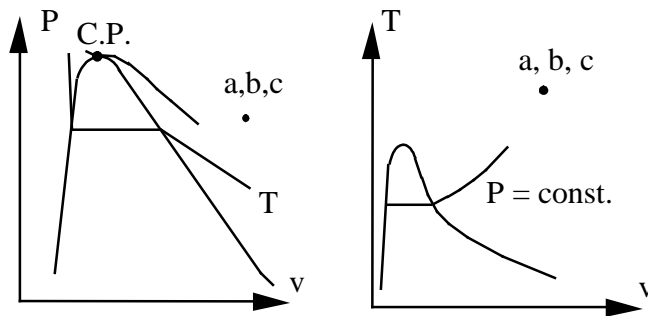
$T > T_c =>$ also $P << P_c$

superheated vapor   assume ideal gas Table A.5

b. Air $T = 20°C$ $P = 200$ kPa   Table A.2

superheated vapor   assume ideal gas Table A.5

c. NH_3 $T = 170°C$ $P = 600$ kPa   Table B.2.2   or A.2

$T > T_c =>$ **superheated vapor**

General Tables

2.25

Give the phase for the following states.

Solution:

    a. H_2O $T = 260°C$ $P = 5$ MPa   Table B.1.1 **or** B.1.2

            B.1.1 For given T read: $P_{sat} = 4.689$ MPa

                  $P > P_{sat}$ => **compressed liquid**

            B.1.2 For given P read: $T_{sat} = 264°C$

                  $T < T_{sat}$ => **compressed liquid**

    b. H_2O $T = -2°C$ $P = 100$ kPa   Table B.1.1 $T < T_{triple\ point}$

            Table B.1.5 at $-2°C$ read: $P_{sat} = 0.518$ kPa

            since $P > P_{sat}$ =>   **compressed solid**

Note state b in P-v, see the
3-D figure, is up on the
solid face.
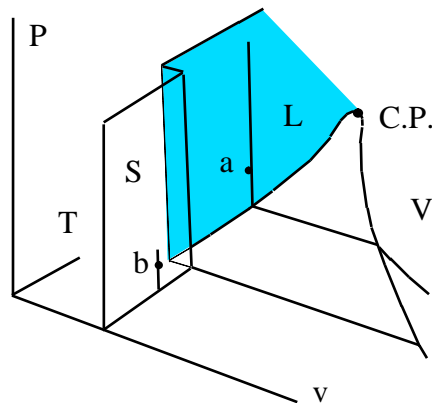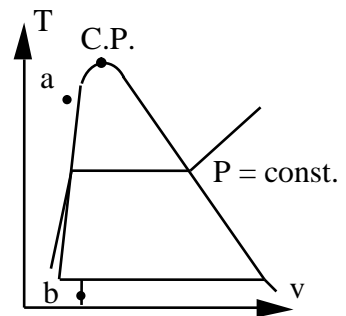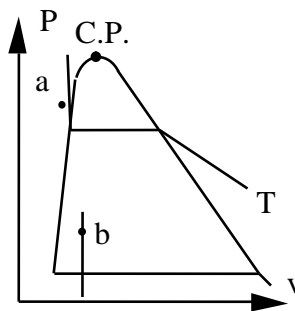
2.26

Determine the phase of the substance at the given state using Appendix B tables

　　　a)　　　Water　　　　　$100°C$, 500 kPa

　　　b)　　　Ammonia　　　$-10°C$, 150 kPa

　　　c)　　　R-410A　　　　　　$0°C$, 350 kPa

Solution:

a) From Table B.1.1　　$P_{sat}(100°C) = 101.3$ kPa

　　　　　500 kPa $> P_{sat}$　then it is　compressed liquid

　　　OR from Table B.1.2　　$T_{sat}(500 \text{ kPa}) = 152°C$

　　　　　$100°C < T_{sat}$　then it is subcooled liquid = compressed liquid

b) Ammonia NH_3 :

　　　　　Table B.2.1: $P < P_{sat}(-10\ °C) = 291$ kPa
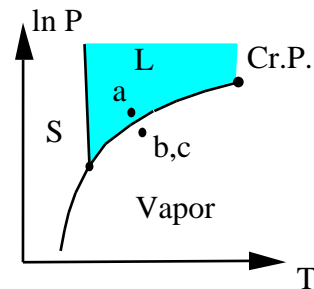
　　　　　Superheated vapor

c) R-410A

　　　　　Table B.4.1: $P < P_{sat}(0\ °C) = 799$ kPa

　　　　　Superheated vapor.

The S-L fusion line goes slightly to the
left for water. It tilts slightly to the right
for most other substances.

2.27

Give the missing property of P-v-T and x for water at

      a. $P = 10$ MPa, $v = 0.003$ m^3/kg   b.   1 MPa, 190°C

      c.   200°C, 0.1 m^3/kg   d.   10 kPa, 10°C

Solution:

For all states start search in table B.1.1 (if T given) or B.1.2 (if P given)

a. $P = 10$ MPa, $v = 0.003$ m^3/kg   so look in B.1.2 at 10 MPa

      $T = 311°C$; $v_f = 0.001452 < v < v_g = 0.01803$ m^3/kg, so L+V

      $\Rightarrow$ $x = (v - v_f)/v_{fg} = (0.003 - 0.001452)/0.01657 = 0.093$

b. 1 MPa, 190°C :   Only one of the two look-ups is needed

      B.1.1: $P < P_{sat} = 1254.4$ kPa so it is superheated vapor

      B.1.2: $T > T_{sat} = 179.91°C$ so it is superheated vapor

      B.1.3: $v = 0.19444 + (0.20596 - 0.19444)\dfrac{190 - 179.91}{200 - 179.91} = 0.2002$ m^3/kg

c. 200°C, 0.1 m^3/kg: look in B.1.1: $P = P_{sat} = 1553.8$ kPa

      $v_f = 0.001156$ m^3/kg $< v <$ $v_g = 0.12736$ m^3/kg, so L+V

      $\Rightarrow$ $x = (v - v_f)/v_{fg} = (0.1 - 0.001156)/0.1262 = 0.7832$
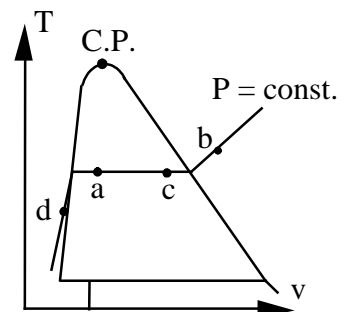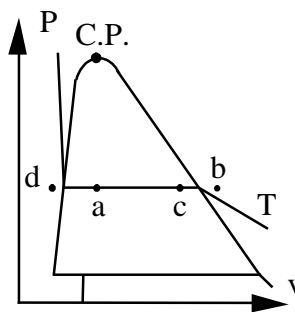
d. 10 kPa, 10°C :   Only one of the two look-ups is needed

      From B.1.1: $P > P_g = 1.2276$ kPa so compressed liquid

      From B.1.2: $T < T_{sat} = 45.8°C$ so compressed liquid

      From B.1.1: $v = v_f = 0.001$ m^3/kg (at given T, not given P)

States shown are
placed relative to the
two-phase region, not
to each other.

2.28

For water at 200 kPa with a quality of 10%, find the volume fraction of vapor.

This is a two-phase state at a given pressure:

Table B.1.2: $v_f = 0.001\ 061\ m^3/kg,\quad v_g = 0.88573\ m^3/kg$

From the definition of quality we get the masses from total mass, m, as

$$m_f = (1-x)\,m, \qquad m_g = x\,m$$

The volumes are

$$V_f = m_f\,v_f = (1-x)\,m\,v_f, \qquad V_g = m_g\,v_g = x\,m\,v_g$$

So the volume fraction of vapor is

$$\text{Fraction} = \frac{V_g}{V} = \frac{V_g}{V_g + V_f} = \frac{x\,m\,v_g}{x\,m\,v_g + (1-x)m\,v_f}$$

$$= \frac{0.1 \times 0.88573}{0.1 \times 0.88573 + 0.9 \times 0.001061} = \frac{0.088573}{0.0895279} = \mathbf{0.9893}$$

Notice that the liquid volume is only about 1% of the total. We could also have found the overall $v = v_f + x v_{fg}$ and then $V = m\,v$.

2.29

Determine whether refrigerant R-410A in each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

Solution:

    All cases are seen in Table B.4.1

a. $50°C$, $0.05 \text{ m}^3/\text{kg}$ From table B.4.1 at $50°C$ $v_g = 0.00707 \text{ m}^3/\text{kg}$

                                      since $v > v_g$ we have **superheated vapor**

b. 1.0 MPa, 20°C   From table B.4.1 at $20°C$ $P_g = 909.9 \text{ kPa}$

                                        since $P < P_g$ we have **superheated vapor**

c. 0.1 MPa, $0.1 \text{ m}^3/\text{kg}$ From table B.4.1 at 0.1 MPa (use 101 kPa)

                                    $v_f = 0.00074$ and $v_g = 0.2395 \text{ m}^3/\text{kg}$

                                    as $v_f < v < v_g$ we have a **mixture of liquid & vapor**

d $-20°C$, 200 kPa   **superheated vapor**, $P < P_g = 400 \text{ kPa}$ at $-20°C$

2.30

Show the states in Problem 2.29 in a sketch of the P-v diagram.

States shown are placed relative to the two-phase region, not to each other.
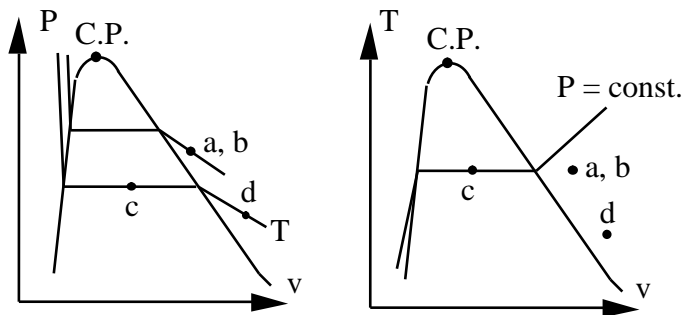
2.31

How great is the change in liquid specific volume for water at 20°C as you move up
from state i towards state j in Fig. 2.14, reaching 15 000 kPa?

State "i", here "a", is saturated liquid and up is then compressed liquid states

a	Table B.1.1:	$v_f = 0.001\ 002\ m^3/kg$	at	2.34 kPa
b	Table B.1.4:	$v_f = 0.001\ 002\ m^3/kg$	at	500 kPa
c	Table B.1.4:	$v_f = 0.001\ 001\ m^3/kg$	at	2000 kPa
d	Table B.1.4:	$v_f = 0.001\ 000\ m^3/kg$	at	5000 kPa
e	Table B.1.4:	$v_f = 0.000\ 995\ m^3/kg$	at	15 000 kPa
f	Table B.1.4:	$v_f = 0.000\ 980\ m^3/kg$	at	50 000 kPa

Notice how small the changes in v are for very large changes in P.
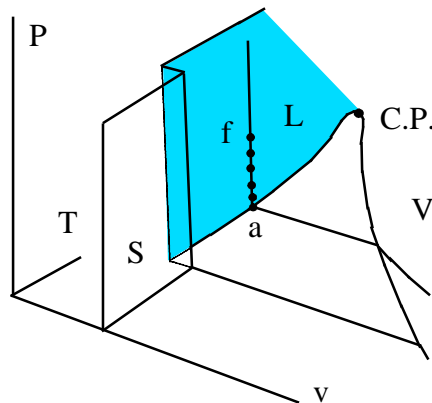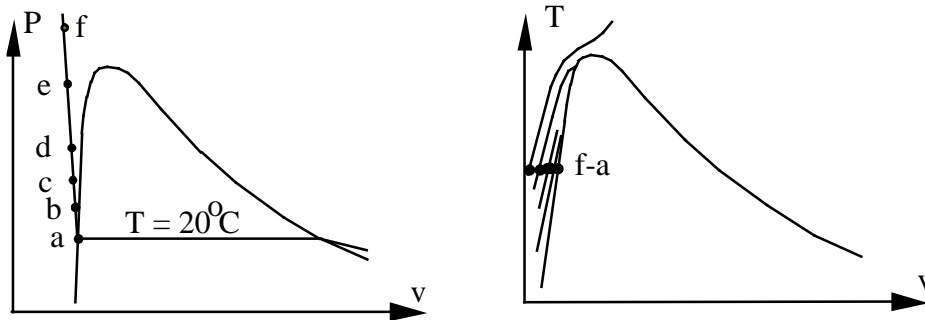
2.32

Fill out the following table for substance ammonia:
Solution:

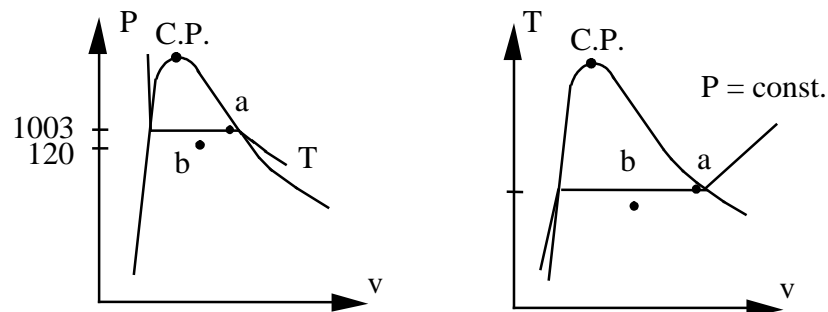|	P [kPa]	T [^{O}C]	v [m^3/kg]	x
a)	**1003**	25	0.1185	**0.9238**
b)	**119.5**	-30	**0.4824**	0.5

a)   B.2.1 $v_f < v < v_g$ => two-phase mix   Look in B.2.1
        => $x = (v - v_f)/v_{fg} = (0.1185 – 0.001658)/0.12647 = 0.9238$

b)   B.2.1 $P = P_{sat} = 119.5$ kPa
           $v = v_f + x\ v_{fg} = 0.001476 + 0.5 \times 0.96192 = 0.4824$ m^3/kg

2.33

Place the two states a-b listed in Problem 2.32 as labeled dots in a sketch of the P-v and T-v diagrams.
Solution:

2.34

Give the missing property of P, T, v and x for R-410A at

a. $T = -20^{\circ}C$, $P = 450$ kPa

b. $P = 300$ kPa, $v = 0.092$ m^3/kg

Solution:

a) B.4.1 $P > P_{sat}$ $= 399.6$ kPa $\Rightarrow$ **compressed liquid**

$v \sim v_f = 0.000803$ m^3/kg

x = undefined

b) B.4.2 $v > v_g$ at 300 kPa $\Rightarrow$ **superheated vapor**

$$T = -20 + [0 - (-20)] \left(\frac{0.092 - 0.08916}{0.09845 - 0.08916} \right) = -13.89^{\circ}C$$

x = undefined
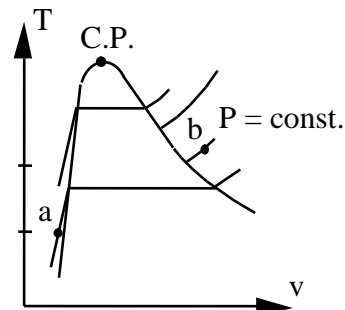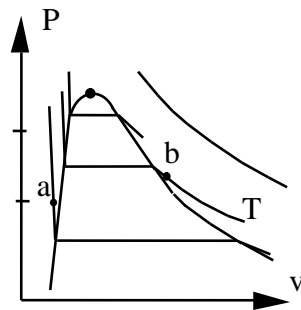
2.35

Fill out the following table for substance water:
Solution:

	P [kPa]	T [$^\circ$C]	v [m^3/kg]	x
a)	500	20	**0.001002**	**Undefined**
b)	500	**151.86**	0.20	**0.532**
c)	1400	200	**0.14302**	**Undefined**
d)	**8581**	300	**0.01762**	0.8

a) Table B.1.1 $P > P_{sat}$ so it is compressed liquid => Table B.1.4

b) Table B.1.2 $v_f < v < v_g$ so two phase   L + V

$$x = \frac{v - v_f}{v_{fg}} = (0.2 - 0.001093) / 0.3738 = 0.532$$

$$T = T_{sat} = 151.86^\circ C$$

c) Only one of the two look-up is needed

Table B.1.1   200°C $P < P_{sat} =$ => superheated vapor

Table B.1.2   1400 kPa $T > T_{sat} = 195^\circ C$

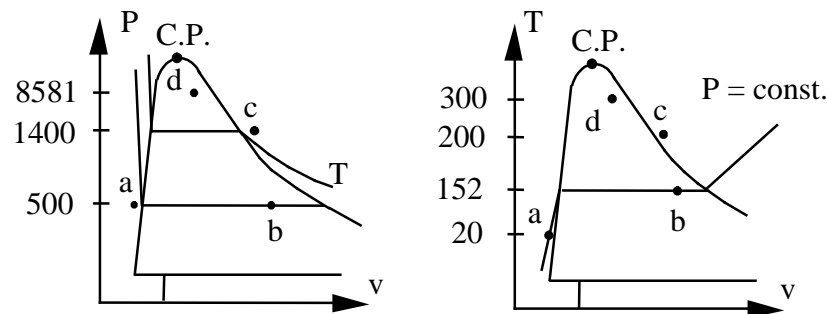Table B.1.3   sub-table for 1400 kPa gives the state properties

d) Table B.1.1   since quality is given it is two-phase

$$v = v_f + x \times v_{fg} = 0.001404 + 0.8 \times 0.02027 = 0.01762 \text{ m}^3/\text{kg}$$

2.36

Place the four states a-d listed in Problem 2.35 as labeled dots in a sketch of the P-v and T-v diagrams.

Solution:

2.37

Determine the specific volume for R-410A at these states:

       a. $-15°C$, 400 kPa

       b.   20°C, 1500 kPa

       c. 20°C, quality 25%

a)   Table B.4.1: $P < P_{sat} = 480.4$ kPa, so superheated vapor.

      B.4.2 $v = 0.06475 + (0.07227 - 0.06475)\dfrac{-15 - (-19.98)}{0 - (-19.98)} = 0.06662 \text{ m}^3/\text{kg}$

b)   Table B.4.1: $P > P_{sat} = 1444$ kPa, so compressed liquid

                  $v \approx v_f = 0.000923 \text{ m}^3/\text{kg}$

c)   Table B.4.1: $v_f = 0.000923 \text{ m}^3/\text{kg}$, $v_{fg} = 0.01666 \text{ m}^3/\text{kg}$ so

          $v = v_f + x\, v_{fg} = 0.000923 + 0.25 \times 0.01666 = 0.00509 \text{ m}^3/\text{kg}$

States shown are
placed relative to the
two-phase region, not
to each other.
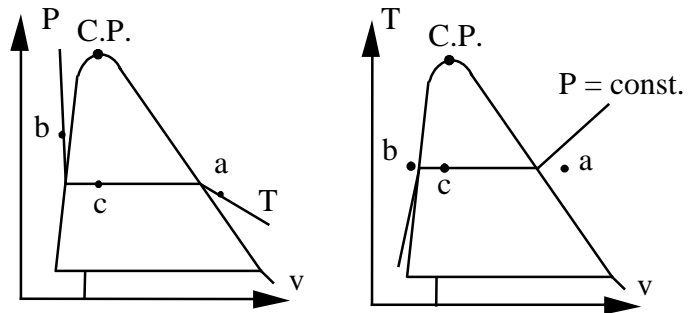
2.38

Give the missing property of P, T, v and x for CH_4 at:

a. $T = 155$ K, $v = 0.04$ m^3/kg
b. $T = 350$ K, $v = 0.25$ m^3/kg
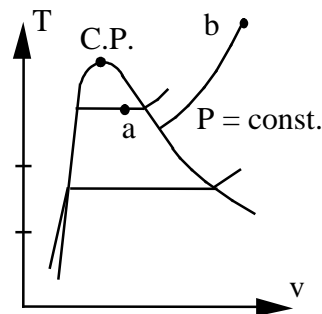
a) B.7.1 $v < v_g = 0.04892$ m^3/kg $\Rightarrow$ 2-phase

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.04 - 0.002877}{0.04605} = \textbf{0.806}$$

$P = P_{sat} = \textbf{1296 kPa}$

b) B.7.1 $T > T_c$ and $v \gg v_c$ $\Rightarrow$ superheated vapor B.7.2
located between 600 & 800 kPa

$$P = 600 + 200 \frac{0.25 - 0.30067}{0.2251 - 0.30067} = \textbf{734 kPa}$$
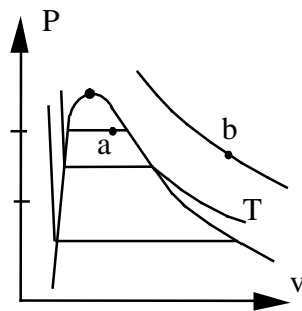
2.39

Give the specific volume of carbon-dioxide at -20°C for 2000 kPa and repeat for 1400 kPa.

Table B.3.1:   -20°C P_{sat} = 1969 kPa,

at 2000 kPa state is compressed liquid: $v = v_f = 0.000969$ m^3/kg

at 1400 kPa state is superheated vapor: $v = 0.0296$ m^3/kg

The 2000 kPa is above and
the 1400 kPa is below
the vaporization line.

2.40

Calculate the following specific volumes

    a. CO_2 $10°C$, 80% quality

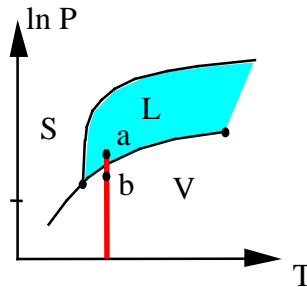   b. Water   4 MPa, 90% quality

    c. Nitrogen   120 K, 60% quality

Solution:

All states are two-phase with quality given. The overall specific volume is given by Eq.2.1 or 2.2

$$v = v_f + x\ v_{fg} = (1\text{-}x)v_f + x\ v_g$$

    a. CO_2 $10°C$, 80% quality in Table B.3.1

$$v = 0.001161 + x \times 0.00624 = 0.006153 \text{ m}^3/\text{kg}$$

    b. Water   4 MPa, 90% quality in Table B.1.2

$$v = 0.001252(1\text{-}x) + x \times 0.04978 = 0.04493 \text{ m}^3/\text{kg}$$

    c. Nitrogen   120 K, 60% quality in Table B.6.1

$$v = 0.001915 + x \times 0.00608 = 0.005563 \text{ m}^3/\text{kg}$$

2.41

Give the missing property of P, T, v, and x for:
   a) R-410A at T = 25°C, v = 0.01 m³/kg
   b) R-410A at 400 kPa, v = 0.075 m³/kg
   c) NH3 at 10°C, v = 0.1 m³/kg

Solution:

a)   Table B.4.1 $v < v_g$ = 0.01514 m³/kg so state is two-phase L + V
        P = P_{sat} = **1653.6 kPa**

$$x = \frac{v - v_f}{v_{fg}} = (0.01 - 0.000944)/0.01420 = \mathbf{0.6377}$$

b)   Table B.4.1 $v > v_g$ so go to B.4.2 superheated vapor 400 kPa.
        Make linear interpolation

$$T = 0 + (20 - 0)\frac{0.075 - 0.07227}{0.07916 - 0.07227} = 7.92, \quad \text{x is undefined}$$

c)   Table B.2.1 $v_f < v < v_g$ = 0.01514 m³/kg so state is two-phase L + V
        P = P_{sat} = **615.2 kPa**

$$x = \frac{v - v_f}{v_{fg}} = (0.1 - 0.0016)/0.20381 = \mathbf{0.4828}$$

Each state is
positioned
relative to the
two-phase region
not to each other
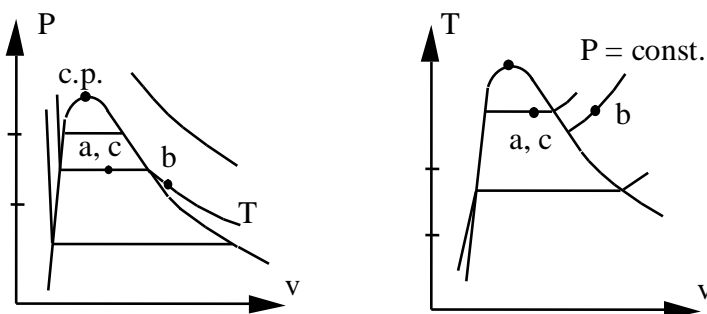
2.42

You want a pot of water to boil at $105^{\circ}C$. How heavy a lid should you put on the 15 cm diameter pot when $P_{atm} = 101$ kPa?

Solution:

Table B.1.1 at $105^{\circ}C$: $P_{sat} = 120.8$ kPa

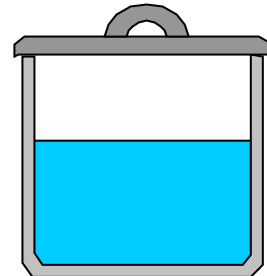$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} 0.15^2 = 0.01767 \text{ m}^2$$

$$F_{net} = (P_{sat} - P_{atm}) A = (120.8 - 101) \text{ kPa} \times 0.01767 \text{ m}^2$$
$$= 0.3498 \text{ kN} = 350 \text{ N}$$

$$F_{net} = m_{lid} \, g$$

$$m_{lid} = F_{net}/g = \frac{350}{9.807} \frac{N}{m/s^2} = \mathbf{35.7 \text{ kg}}$$

Some lids are clamped on, the problem deals with one that stays on due to its weight.
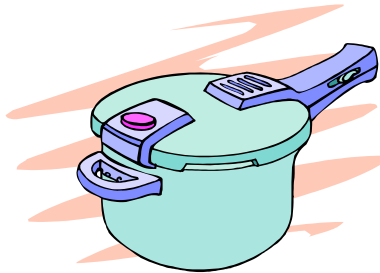
2.43

Water at 400 kPa with a quality of 25% has its pressure raised 50 kPa in a constant volume process. What is the new quality and temperature?

Solution:

State 1 from Table B.1.2 at 400 kPa

$$v = v_f + x\,v_{fg} = 0.001084 + 0.25 \times 0.46138 = 0.11643 \text{ m}^3/\text{kg}$$

State 2 has same v at P = 450 kPa also from Table B.1.2

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.11643 - 0.001088}{0.41289} = \mathbf{0.279}$$

$$T = T_{sat} = \mathbf{147.93 \text{ °C}}$$
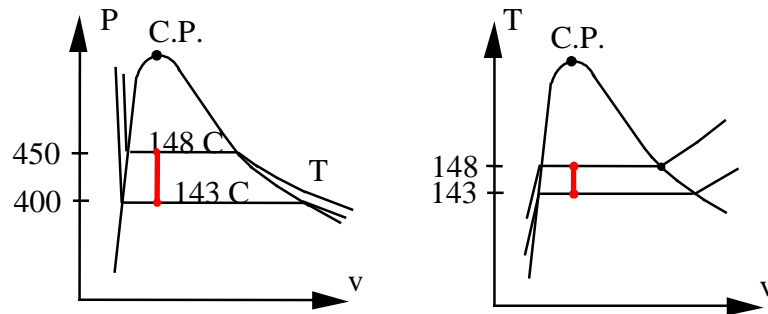
2.44

A sealed rigid vessel has volume of 1 m³ and contains 2 kg of water at 100°C. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 200°C?

Solution:

Process: $v = V/m =$ constant

State 1: $v_1 = 1/2 = 0.5$ m³/kg

from Table B.1.1
it is 2-phase

State 2: 200°C, 0.5 m³/kg
Table B.1.3 between 400
and 500 kPa so interpolate
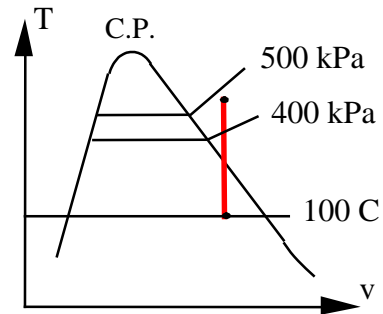
$$P \cong 400 + \frac{0.5 - 0.53422}{0.42492 - 0.53422} \times (500 - 400) = \textbf{431.3 kPa}$$

2.45

Saturated water vapor at 200 kPa is in a constant pressure piston cylinder. At this state the piston is 0.1 m from the cylinder bottom. How much is this distance and the temperature if the water is cooled to occupy half the original volume?

Solution:

State 1:   B 1.2 $v_1 = v_g$ (200 kPa) = 0.8857 m³/kg, T_1 = 120.2°C

Process: P = constant = 200 kPa

State 2:   P, $v_2 = v_1/2 = 0.44285$ m³/kg

Table B.1.2 $v_2 < v_g$ so two phase $T_2 = T_{sat}$ = 120.2°C

Height is proportional to volume

$$h_2 = h_1 \times v_2/v_1 = 0.1 \text{ m} \times 0.5 = \textbf{0.05m}$$
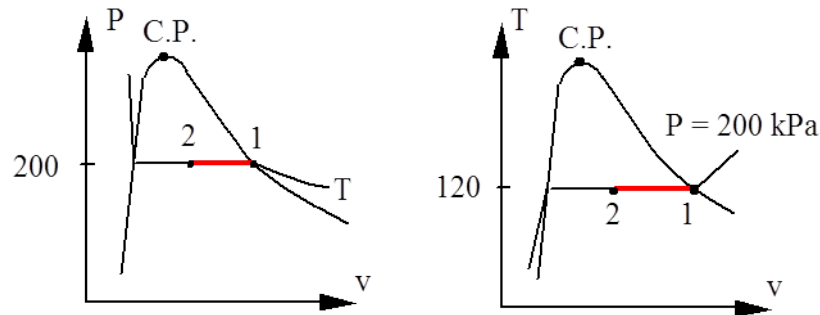
2.46

Saturated liquid water at 60°C is put under pressure to decrease the volume by 1% keeping the temperature constant. To what pressure should it be compressed?

Solution:

State 1: $T = 60°C$, $x = 0.0$;   Table B.1.1: $v = 0.001017$ m^3/kg

Process: $T = $ constant $= 60°C$

State 2:   T, $v = 0.99 \times v_{f (60°C)} = 0.99 \times 0.001017 = 0.0010068$ m^3/kg

Between 20 & 30 MPa in Table B.1.4, $P \cong$ **23.8 MPa**
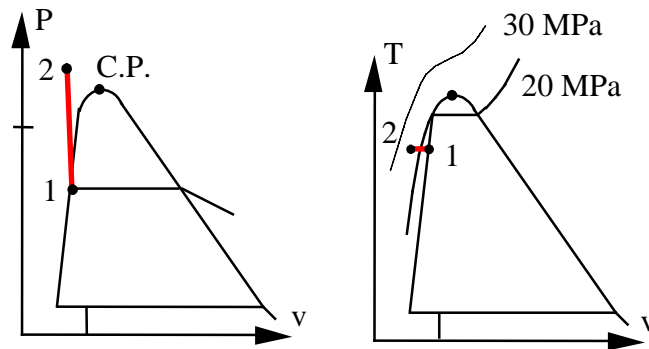
2.47

Water at 400 kPa with a quality of 25% has its temperature raised 20^OC in a constant pressure process. What is the new quality and specific volume?

Solution:

State 1 from Table B.1.2 at 400 kPa

$$v = v_f + x \ v_{fg} = 0.001084 + 0.25 \times 0.46138 = 0.126185 \ m^3/kg$$

State 2 has same P from Table B.1.2 at 400 kPa

$$T_2 = T_{sat} + 20 = 143.63 + 20 = 163.63^O C$$

so state is superheated vapor look in B.1.3 and interpolate between 150 and 200 C in the 400 kPa superheated vapor table.

$$x = \textbf{undefined}$$

$$v_2 = 0.47084 + (0.53422 - 0.47084) \frac{163.63 - 150}{200 - 150} = \textbf{0.4881 m}^3\textbf{/kg}$$
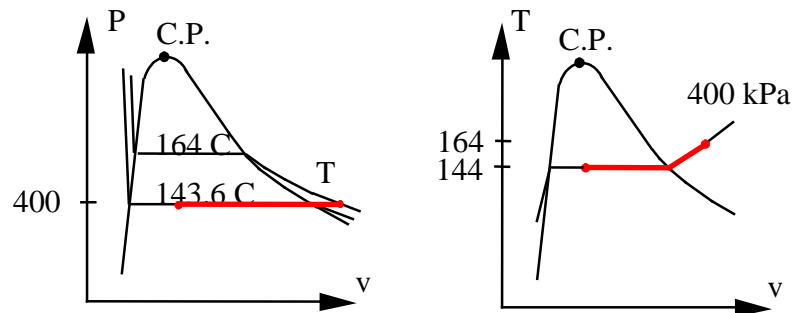
2.48

In your refrigerator the working substance evaporates from liquid to vapor at -20 ^{O}C inside a pipe around the cold section. Outside (on the back or below) is a black grille inside which the working substance condenses from vapor to liquid at +45 ^{O}C. For each location find the pressure and the change in specific volume (v) if the substance is ammonia.

Solution:
The properties come from the saturated tables where each phase change takes place at constant pressure and constant temperature.

Substance	TABLE	T	P_{sat}, kPa	$\Delta v = v_{fg}$, m^3/kg
Ammonia	B.2.1	45 ^{O}C	1782	0.0707
Ammonia	B.2.1	-20 ^{O}C	190	0.622

2.49

Repeat the previous problem with the substances
        a) R-134a   b) R-410A

In your refrigerator, the working substance evaporates from liquid to vapor at -20 $^{\circ}$C inside a pipe around the cold section. Outside (on the back or below) is a black grille inside which the working substanc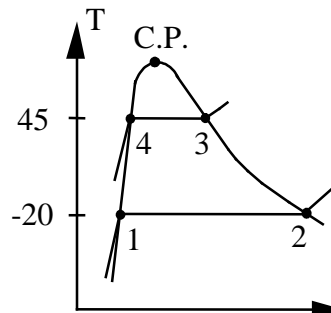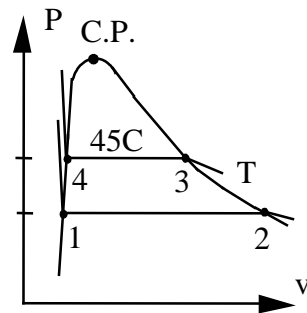e condenses from vapor to liquid at +45 $^{\circ}$C. For each location find the pressure and the change in specific volume (v).

Solution:
The properties come from the saturated tables where each phase change takes place at constant pressure and constant temperature.

Substance	TABLE	T	P_{sat} , kPa	$\Delta v = v_{fg}$, m^3/kg
R-134a	B.5.1	45 $^{\circ}$C	1160	0.0165
R-134a	B.5.1	-20 $^{\circ}$C	134	0.146
R-410A	B.4.1	45 $^{\circ}$C	2728	0.00723
R-410A	B.4.1	-20 $^{\circ}$C	400	0.064
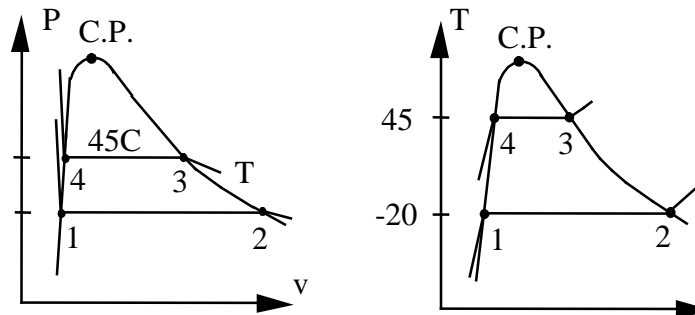
2.50

Repeat Problem 2.48 with CO_2, condenser at $+ 20^{\circ}C$ and evaporator at $-30^{\circ}C$.

Solution:

The properties come from the saturated tables where each phase change takes place at constant pressure and constant temperature.

Substance	TABLE	T	P_{sat} , kPa	$\Delta v = v_{fg}$, m^3/kg
CO_2	B.3.1	$20\ ^{\circ}C$	5729	0.00386
CO_2	B.3.1	$-30\ ^{\circ}C$	1428	0.026
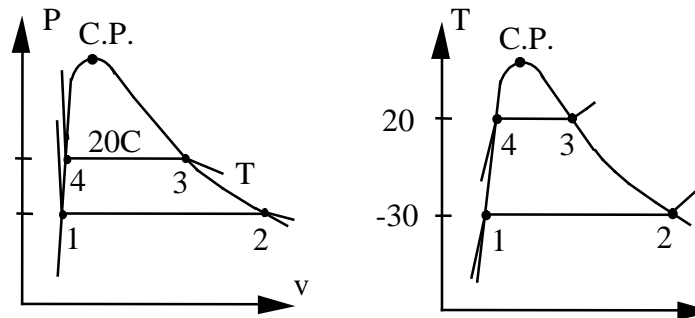
2.51

A glass jar is filled with saturated water at 500 kPa, quality 25%, and a tight lid is put on. Now it is cooled to −10°C. What is the mass fraction of solid at this temperature?

Solution:

Constant volume and mass $\Rightarrow v_1 = v_2 = V/m$

From Table B.1.2: $v_1 = 0.001093 + 0.25 \times 0.3738 = 0.094543 \text{ m}^3/\text{kg}$

From Table B.1.5: $v_2 = 0.0010891 + x_2 \times 446.756 = v_1 = 0.094543 \text{ m}^3/\text{kg}$

$\Rightarrow x_2 = 0.0002$ mass fraction vapor

$x_{solid} = 1 - x_2 = 0.9998$ or   **99.98 %**
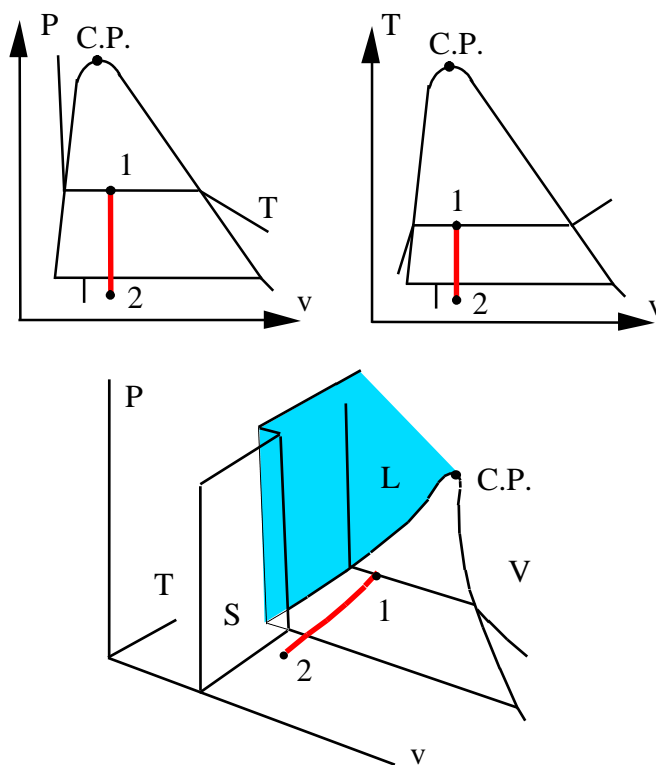
2.52

Two tanks are connected as shown in Fig. P2.52, both containing water. Tank A is at 200 kPa, $v = 0.5$ m^3/kg, $V_A = 1$ m^3 and tank B contains 3.5 kg at 0.5 MPa, 400°C. The valve is now opened and the two come to a uniform state. Find the final specific volume.

Solution:

Control volume: both tanks. Constant total volume and mass process.
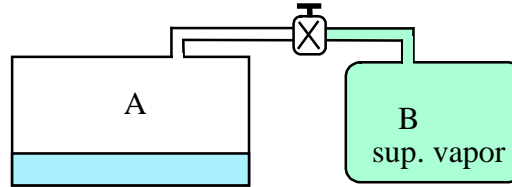
State A1: (P, v) $m_A = V_A/v_A = 1/0.5 = 2$ kg

State B1: (P, T)   Table B.1.3 $v_B = 0.6173$ m^3/kg

$$\Rightarrow V_B = m_B v_B = 3.5 \text{ kg} \times 0.6173 \text{ m}^3/\text{kg} = 2.1606 \text{ m}^3$$

Final state: $m_{tot} = m_A + m_B = 5.5$ kg

$$V_{tot} = V_A + V_B = 3.1606 \text{ m}^3$$

$$v_2 = V_{tot}/m_{tot} = \textbf{0.5746 m}^3\textbf{/kg}$$

2.53

Saturated vapor R-134a at 60°C changes volume at constant temperature. Find the new pressure, and quality if saturated, if the volume doubles. Repeat the question for the case the volume is reduced to half the original volume.

Solution:

1:      (T, x) B.4.1: $v_1 = v_g = 0.01146$ m^3/kg, $P_1 = P_{sat} = 1681.8$ kPa

2:      $v_2 = 2v_1 = 0.02292$ m^3/kg superheated vapor
        Interpolate between 1000 kPa and 1200 kPa
        $$P_2 = 1000 + 200 \times \frac{0.02292 - 0.02311}{0.01844 - 0.02311} = \textbf{1008 kPa}$$

3:      $v_3 = v_1/2 = 0.00573$ m^3/kg $< v_g$: two phase
        $$x_3 = \frac{v_3 - v_f}{v_{fg}} = \frac{0.00573 - 0.000951}{0.01051} = \textbf{0.4547}$$
        $P_3 = P_{sat} = \textbf{1681.8 kPa}$
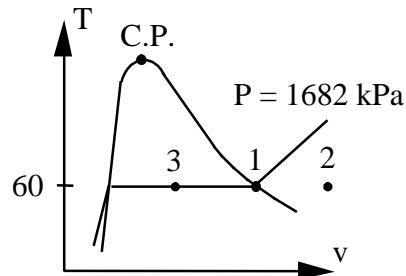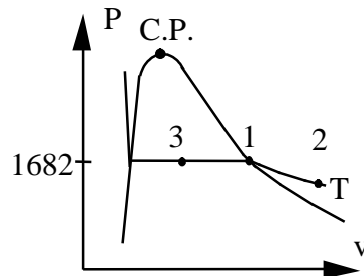
2.54

A steel tank contains 6 kg of propane (liquid + vapor) at 20°C with a volume of 0.015 m^3. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 1 kg instead of 6 kg?

Solution:

Constant volume and mass $v_2 = v_1 = \dfrac{V}{m} = \dfrac{0.015 \text{ m}^3}{6 \text{ kg}} = 0.0025 \text{ m}^3/\text{kg}$
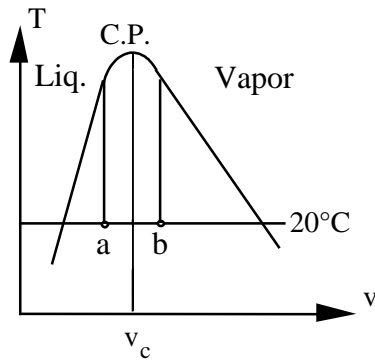
A.2: $v_c = 0.00454 \text{ m}^3/\text{kg} > v_1$

eventually reaches sat. liquid.
   $\Rightarrow$ **level rises to top**

If m = 1 kg $\Rightarrow$ $v_1 = 0.015 \text{ m}^3/\text{kg} > v_c$

then it will reach saturated vapor.
   $\Rightarrow$ **level falls**

2.55

Saturated water vapor at 60°C has its pressure decreased to increase the volume by 10% keeping the temperature constant. To what pressure should it be expanded?

Solution:

Initial state: $v = 7.6707$ m^3/kg   from table B.1.1

Final state: $v = 1.10 \times v_g = 1.1 \times 7.6707 = 8.4378$ m^3/kg

Interpolate at 60°C between saturated (P = 19.94 kPa) and superheated vapor P = 10 kPa in Tables B.1.1 and B.1.3

$$P \cong 19.941 + (10 - 19.941)\frac{8.4378 - 7.6707}{15.3345 - 7.6707} = \textbf{18.9 kPa}$$
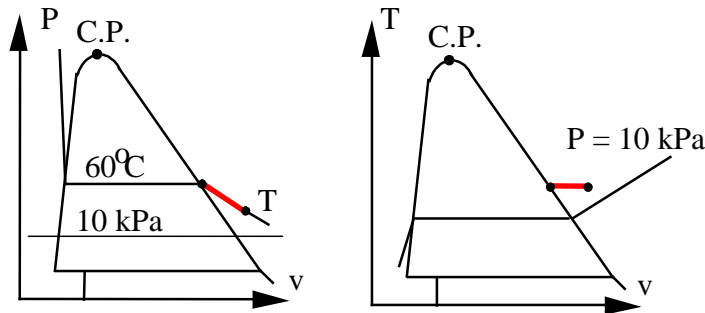
Comment: T,v $\Rightarrow$ P = 18 kPa (software) v is not linear in P, more like 1/P, so the linear interpolation in P is not very accurate.

2.56

Ammonia at 20^OC with a quality of 50% and total mass 2 kg is in a rigid tank with an outlet valve at the top. How much vapor (mass) can you take out through the valve assuming the temperature stays constant?

Solution:

The top has saturated vapor at 20^OC as long as there is a two phase inside. When there is no more liquid and vapor will be taken out pressure will drop for the remaining vapor so we can take it out until we reach P_0.

$$V = m_1 v_1 = 2 \text{ kg} \times 0.5 \, (0.001638 + 0.14922) \text{ m}^3/\text{kg} = 0.15086 \text{ m}^3$$

$$v_2 = 1.4153 \text{ m}^3/\text{kg} \quad \text{(from Table B.2.2 at 100 kPa)}$$

$$m_2 = V/v_2 = 0.15086 \text{ m}^3/ \, 1.4153 \text{ m}^3/\text{kg} = 0.1066 \text{ kg}$$

$$m = m_1 - m_2 = 2 - 0.1066 = \textbf{1.893 kg}$$
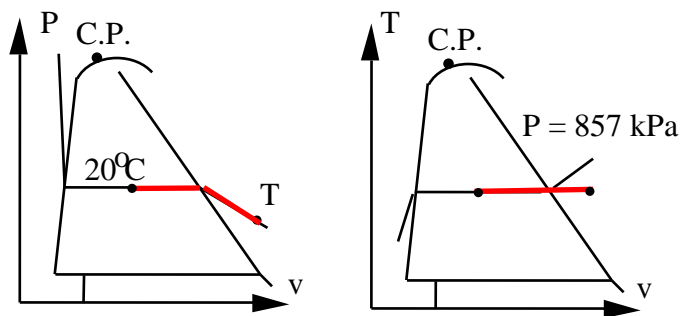
2.57

A sealed rigid vessel of 2 m^3 contains a saturated mixture of liquid and vapor R-134a at 10°C. If it is heated to 50°C, the liquid phase disappears. Find the pressure at 50°C and the initial mass of the liquid.

Solution:

Process: constant volume and constant mass.

P

2

1

v
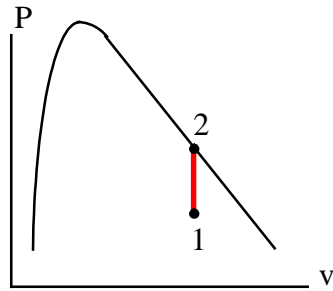
State 2 is saturated vapor, from table B.5.1

$$P_2 = P_{sat}(50°C) = \textbf{1.318 MPa}$$

State 1: same specific volume as state 2

$v_1 = v_2 = 0.015124$ m^3/kg

$v_1 = 0.000794 + x_1 \times 0.048658$

$\Rightarrow x_1 = 0.2945$

$m = V/v_1 = 2$ m^3/0.015124 m^3/kg $= 132.24$ kg;

$m_{liq} = (1 - x_1)$ m $= \textbf{93.295 kg}$

2.58

A storage tank holds methane at 120 K, with a quality of 25 %, and it warms up by 5°C per hour due to a failure in the refrigeration system. How long time will it take before the methane becomes single phase and what is the pressure then?

Solution: Use Table B.7.1

Assume rigid tank $v = $ constant $= v_1$

$v_1 = 0.002439 + 0.25 \times 0.30367$

$\quad = 0.078366 \ m^3/kg$

We then also see that

$v_1 \ > \ v_c = 0.00615 \ m^3/kg$

All single phase when

$v = v_g \ => \ T \cong \ 145 \ K$
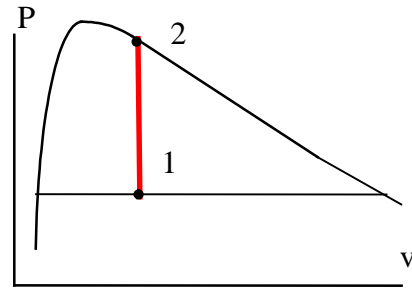
$\Delta t = \dfrac{\Delta T}{(5°C/h)} \cong \dfrac{145 - 120}{5} = $ **5 hours;** $P = P_{sat} = $ **824 kPa**

2.59

Ammonia at 10°C and mass 10 kg is in a piston cylinder with an initial volume of 1 m^3. The piston initially resting on the stops has a mass such that a pressure of 900 kPa will float it. Now the ammonia is slowly heated to 50°C. Find the final pressure and volume.

Solution:

C.V. Ammonia, constant mass.

Process: V = constant, unless $P = P_{float}$

State 1: T = 10 $^{\circ}$C,

$$v_1 = \frac{V}{m} = \frac{1}{10} = 0.1 \text{ m}^3/\text{kg}$$

From Table B.2.1 $v_f < v < v_g$

$$x_1 = \frac{v - v_f}{v_{fg}} = \frac{0.1 - 0.0016}{0.20381} = 0.4828$$
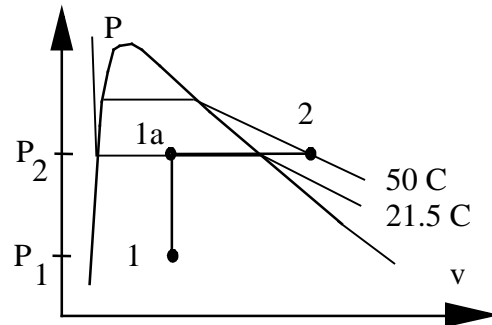
State 1a: P = 900 kPa, $v = v_1 = 0.1$ m^3/kg $< v_g$ at 900 kPa

This state is two-phase $T_{1a} = 21.52^{\circ}$C

Since $T_2 > T_{1a}$ then $v_2 > v_{1a}$

State 2: 50°C and on line(s) means

$P_2 =$ **900 kPa** which is superheated vapor.

Table B.2.2 : $v_2 = (0.18465 + 0.14499)/2 = 0.16482$ m^3/kg

$V_2 = mv_2 =$ **1.6482 m^3**

2.60

A 400-m^3 storage tank is being constructed to hold LNG, liquified natural gas, which may be assumed to be essentially pure methane. If the tank is to contain 90% liquid and 10% vapor, by volume, at 100 kPa, what mass of LNG (kg) will the tank hold? What is the quality in the tank?

Solution:

CH$_4$ is in the section B tables.

From Table B.7.1: $v_f \cong 0.002366$ m^3/kg,   (interpolated)

From Table B.7.2: $v_g \cong 0.55665$ m^3/kg   (first entry 100 kPa)

$$m_{liq} = \frac{V_{liq}}{v_f} = \frac{0.9 \times 400}{0.002366} = 152\ 155.5 \text{ kg}; \quad m_{vap} = \frac{V_{vap}}{v_g} = \frac{0.1 \times 400}{0.55665} = 71.86 \text{ kg}$$

$$m_{tot} = \mathbf{152\ 227\ kg}, \quad x = m_{vap} / m_{tot} = \mathbf{4.72 \times 10^{-4}}$$

2.61

A boiler feed pump delivers 0.05 m^3/s of water at 240°C, 20 MPa. What is the mass flowrate (kg/s)? What would be the percent error if the properties of saturated liquid at 240°C were used in the calculation? What if the properties of saturated liquid at 20 MPa were used?

Solution:

State 1:   (T, P) compressed liquid seen in B.1.4: $v = 0.001205$ m^3/kg

$\dot{m} = \dot{V}/v = 0.05/0.001205 = $ **41.5 kg/s**

$v_{f\,(240°C)} = 0.001229$ m^3/kg $\Rightarrow \dot{m} = 40.68$ kg/s **error 2%**

$v_{f\,(20\,MPa)} = 0.002036$ m^3/kg $\Rightarrow \dot{m} = 24.56$ kg/s **error 41%**
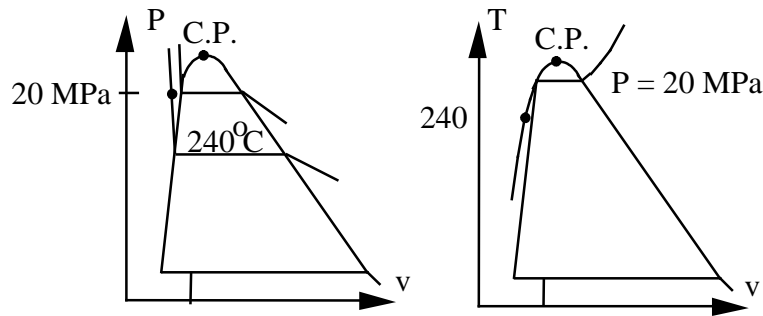
The constant T line is nearly vertical for the liquid phase in the P-v diagram.
The state is at so high P, T that the saturated liquid line is not extremely steep.

2.62

A piston/cylinder arrangement is loaded with a linear spring and the outside atmosphere. It contains water at 5 MPa, 400°C with the volume being 0.1 m^3. If the piston is at the bottom, the spring exerts a force such that P_{lift} = 200 kPa. The system now cools until the pressure reaches 1200 kPa. Find the mass of water, the final state (T_2, v_2) and plot the P–v diagram for the process.

Solution:

P

5000

1200

200

2

1

a

0   ?   0.05781

v
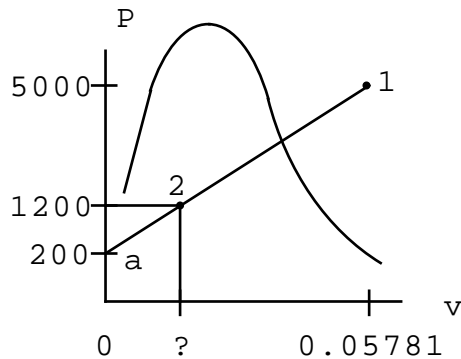
1: Table B.1.3 $\Rightarrow$ $v_1 = 0.05781$ m^3/kg

$m = V/v_1 = 0.1/0.05781 = 1.73$ kg

Straight line: $P = P_a + C \times v$

$$v_2 = v_1 \frac{P_2 - P_a}{P_1 - P_a} = \textbf{0.01204 m}^3\textbf{/kg}$$

$v_2 < v_g$(1200 kPa) so two-phase $T_2 = \textbf{188°C}$

$\Rightarrow x_2 = (v_2 - 0.001139)/0.1622 = 0.0672$

2.63

A pressure cooker (closed tank) contains water at 100°C with the liquid volume being 1/20 of the vapor volume. It is heated until the pressure reaches 2.0 MPa. Find the final temperature. Has the final state more or less vapor than the initial state?

Solution:

State 1: $\qquad V_f = m_f\, v_f = V_g/20 = m_g v_g/20$;

$\qquad$ Table B.1.1: $\quad v_f = 0.001044\ m^3/kg, \quad v_g = 1.6729\ m^3/kg$

$$x_1 = \frac{m_g}{m_g + m_f} = \frac{20\ m_f v_f\,/\,v_g}{m_f + 20\ m_f v_f\,/\,v_g} = \frac{20\ v_f}{20\ v_f + v_g} = \frac{0.02088}{0.02088 + 1.6729} = 0.01233$$

$v_1 = 0.001044 + 0.01233 \times 1.67185 = 0.02166\ m^3/kg$

State 2: $\quad v_2 = v_1 = 0.02166\ m^3/kg\ < v_g(2MPa)$ from B.1.2 so two-phase
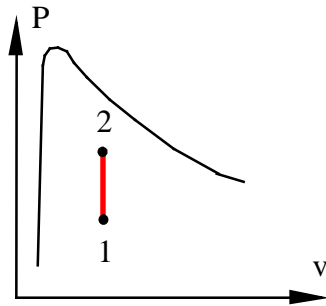
At state 2: $\qquad v_2 = v_f + x_2\, v_{fg}$

$\qquad 0.02166 = 0.001177 + x_2 \times 0.09845$

$\qquad \Rightarrow\ \ x_2 = 0.208$

More vapor at final state

$T_2 = T_{sat}(2MPa) = \mathbf{212.4°C}$

2.64

A pressure cooker has the lid screwed on tight. A small opening with A = 5 mm^2 is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at 120°C with an outside atmosphere at 101.3 kPa?

Table B.1.1.: P_{sat} = 198.5 kPa

$F = mg = \Delta P \times A$
$m = \Delta P \times A/g$
$$= \frac{(198.5\text{-}101.3)\times1000\times5\times10^{-6}}{9.807} \frac{N}{ms^{-2}}$$
$= 0.0496$ kg = **50 g**
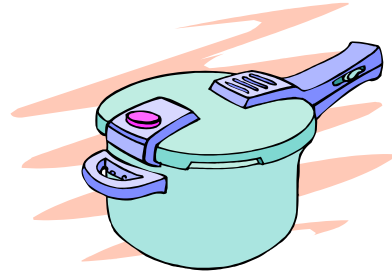
Ideal Gas Law

2.65

What is the relative (%) change in P if we double the absolute temperature of an ideal gas keeping mass and volume constant? What will it be if we double V having m, T constant.

Ideal gas law: $PV = mRT$

State 2: $P_2V = mRT_2 = mR2T_1 = 2P_1V$ $\Rightarrow$ $P_2 = 2P_1$
           Relative change $= \Delta P/P_1 = P_1/P_1 = 1 = $ **100%**

State 3: $P_3V_3 = mRT_1 = P_1V_1$ $\Rightarrow$ $P_3 = P_1V_1/V_3 = P_1/2$
           Relative change $= \Delta P/P_1 = -P_1/2P_1 = -0.5 = $ **-50%**
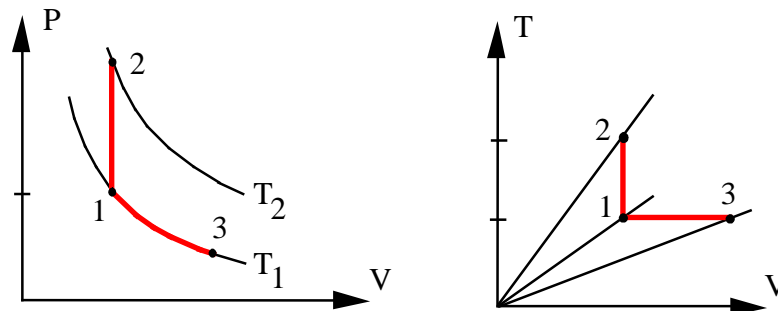
2.66

A 1-m^3 tank is filled with a gas at room temperature 20°C and pressure 200 kPa. How much mass is there if the gas is a) air, b) neon or c) propane ?

Solution:

Use Table A.2 to compare T and P to the critical T and P with

$T = 20°C = 293.15$ K ; $P = 200$ kPa $<< P_c$ for all

Air : $T >> T_{C,N2}$; $T_{C,O2} = 154.6$ K   so ideal gas; R= 0.287 kJ/kg K

Neon: $T >> T_c = 44.4$ K   so ideal gas; R = 0.41195 kJ/kg K

Propane: $T < T_c = 370$ K, but $P << P_c = 4.25$ MPa

so gas R = 0.18855 kJ/kg K

All states are ideal gas states so the ideal gas law applies

$$PV = mRT$$

a) $m = \dfrac{PV}{RT} = \dfrac{200 \text{ kPa} \times 1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 293.15 \text{ K}} = \textbf{2.377 kg}$

b) $m = \dfrac{PV}{RT} = \dfrac{200 \text{ kPa} \times 1 \text{ m}^3}{0.41195 \text{ kJ/kgK} \times 293.15 \text{ K}} = \textbf{1.656 kg}$

c) $m = \dfrac{PV}{RT} = \dfrac{200 \text{ kPa} \times 1 \text{ m}^3}{0.18855 \text{ kJ/kgK} \times 293.15 \text{ K}} = \textbf{3.618 kg}$

2.67

   Calculate the ideal gas constant for argon and hydrogen based on table A.2 and
   verify the value with Table A.5

argon: $R = \dfrac{\bar{R}}{M} = \dfrac{8.3145}{39.948} = 0.2081 \text{ kJ/kgK}$ same as Table A.5

hydrogen: $R = \dfrac{\bar{R}}{M} = \dfrac{8.3145}{2.016} = 4.124256 \text{ kJ/kgK}$ same as Table A.5

2.68

A pneumatic cylinder (a piston cylinder with air) must close a door with a force of 500 N. The cylinder cross-sectional area is 5 cm^2. With V = 50 cm^3, T = 20°C, what is the air pressure and its mass?

$$F = PA - P_oA \Rightarrow$$

$$P = P_o + F/A = 100 \text{ kPa} + \frac{500 \text{ N}}{0.0005 \text{ m}^2 \times 1000 \text{ N/kN}} = \textbf{1100 kPa}$$

$$m = \frac{P_1V_1}{RT_1} = \frac{1100 \text{ kPa} \times 0.00005 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 293 \text{ K}} = \textbf{0.00065 kg = 0.65 g}$$

Comment: Dependent upon your understanding of the problem you could also have neglected the atmospheric pressure to get 1000 kPa and 0.59 g for answers.

2.69

Is it reasonable to assume that at the given states the substance behaves as an ideal gas?

Solution:

a) Oxygen, O_2 at   30°C, 3 MPa   **Ideal Gas** (T » T_c = 155 K from A.2)

b) Methane, CH_4 at   30°C, 3 MPa   **Ideal Gas** (T » T_c = 190 K from A.2)

c) Water, H_2O at   30°C, 3 MPa   **NO** compressed liquid $P > P_{sat}$ (B.1.1)

d) R-134a   at   30°C, 3 MPa   **NO** compressed liquid $P > P_{sat}$ (B.5.1)

e) R-134a   at   30°C, 100 kPa   **Ideal Gas**   P is low $< P_{sat}$ (B.5.1)
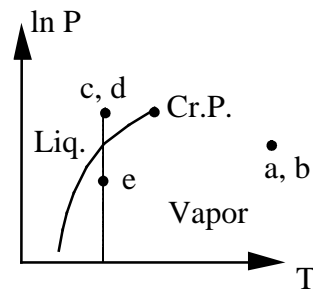
2.70

Helium in a steel tank is at 250 kPa, 300 K with a volume of 0.1 m^3. It is used to fill a balloon and when the pressure drops to 125 kPa, the flow of helium stops by itself. If all the helium still is at 300 K, how big a balloon did I get?

Solution:

State 1:   m = V/v   assume ideal gas so

$$m = \frac{P_1 V_1}{RT_1} = \frac{250 \text{ kPa} \times 0.1 \text{ m}^3}{2.0771 \text{ kJ/kgK} \times 300 \text{ K}}$$
$$= 0.0401 \text{ kg}$$

State 2:   Same mass so then (T$_2$ = T$_1$)

$$V_2 = \frac{mRT_2}{P_2} = \frac{P_1 V_1}{RT_1} \frac{RT_2}{P_2} = V_1 \frac{P_1}{P_2} = 0.1 \text{ m}^3 \frac{250}{125} = 0.2 \text{ m}^3$$

The balloon volume is
$$V_{balloon} = V_2 - V_1 = 0.2 - 0.1 = \textbf{0.1 m}^3$$
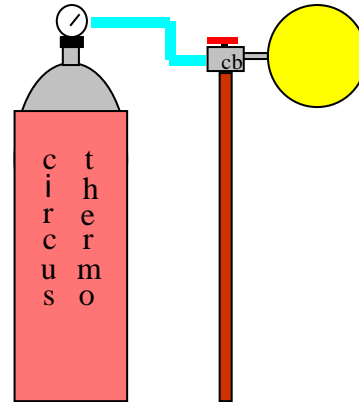
2.71

A hollow metal sphere of 150-mm inside diameter is weighed on a precision beam balance when evacuated and again after being filled to 875 kPa with an unknown gas. The difference in mass is 0.0025 kg, and the temperature is 25°C. What is the gas, assuming it is a pure substance listed in Table A.5 ?

Solution:

Assume an ideal gas with total volume: $V = \dfrac{\pi}{6}(0.15)^3 = 0.001767 \ m^3$

$$M = \frac{m\bar{R}T}{PV} = \frac{0.0025 \ kg \times 8.3145 \ kJ/kmol\text{-}K \times 298.2 \ K}{875 \ kPa \times 0.001767 \ m^3}$$

$$= \textbf{4.009} \ kg/kmol \approx M_{He}$$

$$\Rightarrow \quad \textbf{Helium Gas}$$

2.72

A spherical helium balloon of 10 m in diameter is at ambient T and P, 15°C and 100 kPa. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?

We need to find the masses and the balloon volume

$$V = \frac{\pi}{6} D^3 = \frac{\pi}{6} 10^3 = 523.6 \text{ m}^3$$

$$m_{He} = \rho V = \frac{V}{v} = \frac{PV}{RT} = \frac{100 \text{ kPa} \times 523.6 \text{ m}^3}{2.0771 \text{ kJ/kgK} \times 288 \text{ K}} = \mathbf{87.5 \text{ kg}}$$

$$m_{air} = \frac{PV}{RT} = \frac{100 \text{ kPa} \times 523.6 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 288 \text{ K}}$$
$$= 633 \text{ kg}$$

$$m_{lift} = m_{air} - m_{He} = 633\text{-}87.5 = \mathbf{545.5 \text{ kg}}$$

2.73

A glass is cleaned in 45°C hot water and placed on the table bottom up. The room air at 20°C that was trapped in the glass gets heated up to 40°C and some of it leaks out so the net resulting pressure inside is 2 kPa above ambient pressure of 101 kPa. Now the glass and the air inside cools down to room temperature. What is the pressure inside the glass?

Solution:

1 air: 40°C, 103 kPa

2 air: 20°C,   ?

Slight amount
of liquid water
seals to table top

AIR

Constant Volume: $V_1 = V_2$,

Constant Mass $m_1 = m_2$

Ideal Gas $P_1V_1 = m_1RT_1$ and $P_2V_2 = m_1RT_2$

Take Ratio

$$P_2 = P_1 \frac{T_1}{T_2} = 103 \text{ kPa} \times \frac{20 + 273}{40 + 273} = \textbf{96.4 kPa}$$
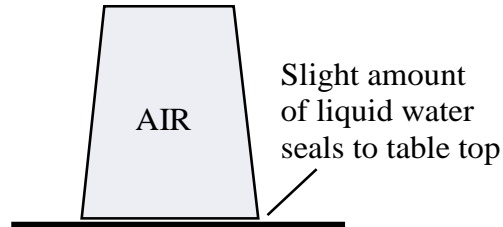
This is a vacuum relative to atm pressure so the glass is pressed against table.

2.74

Air in an internal combustion engine has 227°C, 1000 kPa with a volume of 0.1 m^3. Now combustion heats it to 1800 K in a constant volume process. What is the mass of air and how high does the pressure become?

The mass comes from knowledge of state 1 and ideal gas law

$$m = \frac{P_1 V_1}{RT_1} = \frac{1000 \text{ kPa} \times 0.1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times (227 + 273) \text{ K}} = \textbf{0.697 kg}$$

The final pressure is found from the ideal gas law written for state 1 and state 2 and then eliminate the mass, gas constant and volume ($V_2 = V_1$) between the equations

$$P_1 \, V_1 = m \, RT_1 \qquad \text{and} \qquad P_2 \, V_2 = m \, RT_2$$

$$P_2 = P_1 \times T_2/T_1 = 1000 \text{ kPa} \times \frac{1800}{500} = \textbf{3600 kPa}$$

2.75

Air in an automobile tire is initially at $-10°C$ and 190 kPa. After the automobile is driven awhile, the temperature gets up to $10°C$. Find the new pressure. You must make one assumption on your own.

Solution:

Assume constant volume $V_2 = V_1$ and that air is an ideal gas

$$P_1 V_1 = mRT_1 \quad \text{and} \quad P_2 V_2 = mRT_2$$

so

$$P_2 = P_1 \times T_2/T_1$$

$$= 190 \text{ kPa} \times \frac{283.15}{263.15} = \textbf{204.4 kPa}$$
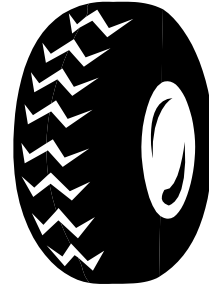
2.76

A rigid tank of 1 m^3 contains nitrogen gas at 600 kPa, 400 K. By mistake someone lets 0.5 kg flow out. If the final temperature is 375 K what is the final pressure?

Solution:

$$m = \frac{PV}{RT} = \frac{600 \text{ kPa} \times 1 \text{ m}^3}{0.2968 \text{ kJ/kgK} \times 400 \text{ K}} = 5.054 \text{ kg}$$

$$m_2 = m - 0.5 = 4.554 \text{ kg}$$

$$P_2 = \frac{m_2 R T_2}{V} = \frac{4.554 \text{ kg} \times 0.2968 \text{ kJ/kgK} \times 375 \text{ K}}{1 \text{ m}^3} = \textbf{506.9 kPa}$$

2.77

Assume we have 3 states of saturated vapor R-134a at +40 $^{\circ}$C, 0 $^{\circ}$C and –40 $^{\circ}$C. Calculate the specific volume at the set of temperatures and corresponding saturated pressure assuming ideal gas behavior. Find the percent relative error = $100(v - v_g)/v_g$ with v_g from the saturated R-134a table.

Solution:

R-134a.   Table values from Table B.5.1 P_{sat}, $v_g(T)$

Ideal gas constant from Table A.5: $R_{R-134a} = 0.08149$ kJ/kg K

T	P_{sat} , kPa	v_g, m^3/kg	$v_{ID.G.} = RT / P_{sat}$	error %
-40 $^{\circ}$C	51.8	0.35696	0.36678	2.75
0 $^{\circ}$C	294	0.06919	0.07571	9.4
40 $^{\circ}$C	1017	0.02002	0.02509	25.3
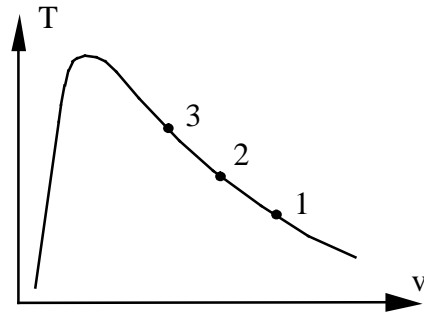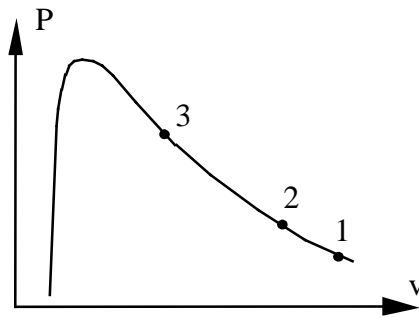
2.78

Do Problem 2.77 for R-410A.

Solution:

R-410A.   Table values from Table B.4.1 P_{sat}, $v_g(T)$

Ideal gas constant from Table A.5: $R_{R-410a} = 0.1146$ kJ/kg K

T	P_{sat} , kPa	v_g, m³/kg	$v_{ID.G.} = RT / P_{sat}$	error %
-40 °C	175.0	0.14291	0.1527	6.8
0 °C	798.7	0.03267	0.03919	20
40 °C	2420.7	0.00967	0.01483	53.3
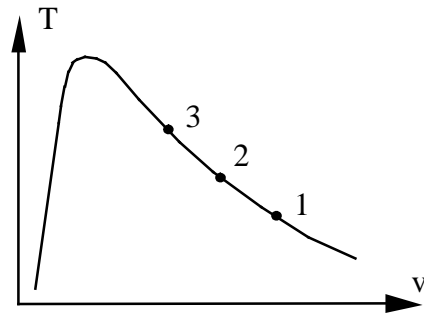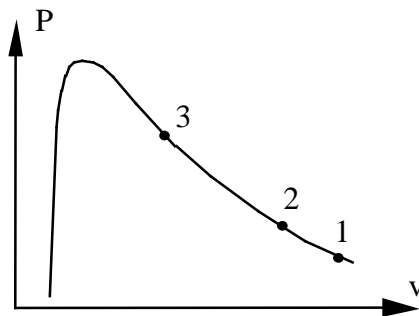
2.79

Do Problem 2.77 for the substance ammonia.

Solution:

NH3.   Table values from Table B.2.1 P_{sat}, v_g(T)

Ideal gas constant from Table A.5: $R_{ammonia}$ = 0.4882 kJ/kg K

T	P_{sat} , kPa	v_g, m^3/kg	$v_{ID.G.}$ = RT / P_{sat}	error %
-40 ^{o}C	71.7	1.5526	1.5875	2.25
0 ^{o}C	429.6	0.28929	0.3104	7.3
40 ^{o}C	1555	0.08313	0.09832	18.3
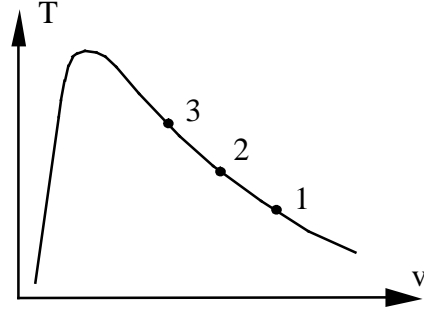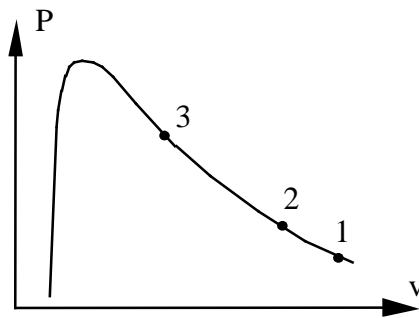
2.80

A 1 m^3 rigid tank has propane at 100 kPa, 300 K and connected by a valve to another tank of 0.5 m^3 with propane at 250 kPa, 400 K. The valve is opened and the two tanks come to a uniform state at 325 K. What is the final pressure?

Solution:

Propane is an ideal gas (P << P$_c$) with R = 0.1886 kJ/kgK from Tbl. A.5

$$m_A = \frac{P_A V_A}{RT_A} = \frac{100 \text{ kPa} \times 1 \text{ m}^3}{0.1886 \text{ kJ/kgK} \times 300 \text{ K}} = 1.7674 \text{ kg}$$

$$m_B = \frac{P_B V_B}{RT_B} = \frac{250 \text{ kPa} \times 0.5 \text{ m}^3}{0.1886 \text{ kJ/kgK} \times 400 \text{ K}} = 1.6564 \text{ kg}$$

$$V_2 = V_A + V_B = 1.5 \text{ m}^3$$

$$m_2 = m_A + m_B = 3.4243 \text{ kg}$$

$$P_2 = \frac{m_2 R T_2}{V_2} = \frac{3.4243 \text{ kg} \times 0.1886 \text{ kJ/kgK} \times 325 \text{ K}}{1.5 \text{ m}^3} = \textbf{139.9 kPa}$$

2.81

A vacuum pump is used to evacuate a chamber where some specimens are dried at 50°C. The pump rate of volume displacement is 0.5 m^3/s with an inlet pressure of 0.1 kPa and temperature 50°C. How much water vapor has been removed over a 30-min period?

Solution:

Use ideal gas since   P $<<$ lowest P in steam tables.

From table A.5 we get   R = 0.46152 kJ/kg K

m = $\dot{m}$ Δt   with mass flow rate as: $\dot{m}$= $\dot{V}$/v = P$\dot{V}$/RT   (ideal gas)

$\Rightarrow$ m = P$\dot{V}\Delta$t/RT = $\dfrac{0.1 \text{ kPa} \times 0.5 \text{ m}^3/\text{s} \times 30 \text{ min} \times 60 \text{ s/min}}{0.46152 \text{ kJ/kgK} \times 323.15 \text{ K}}$ = **0.603 kg**

2.82

A 1-m^3 rigid tank with air at 1 MPa, 400 K is connected to an air line as shown in Fig. P2.82. The valve is opened and air flows into the tank until the pressure reaches 5 MPa, at which point the valve is closed and the temperature inside is 450K.

   a. What is the mass of air in the tank before and after the process?

   b. The tank eventually cools to room temperature, 300 K. What is the pressure inside the tank then?

Solution:

P, T known at both states and assume the air behaves as an ideal gas.

$$m_{air1} = \frac{P_1 V}{RT_1} = \frac{1000 \text{ kPa} \times 1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 400 \text{ K}} = \textbf{8.711 kg}$$

$$m_{air2} = \frac{P_2 V}{RT_2} = \frac{5000 \text{ kPa} \times 1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 450 \text{ K}} = \textbf{38.715 kg}$$

Process 2 → 3 is constant V, constant mass cooling to T_3

$$P_3 = P_2 \times (T_3/T_2) = 5000 \text{ kPa} \times (300/450) = \textbf{3.33 MPa}$$

2.83

A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 20°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

Solution:

Assume CO_2 is an ideal gas, table A.5:   R = 0.1889 kJ/kg K

$$V_{cyl} = A \times L = \frac{\pi}{4}(0.2)^2 \times 1 = 0.031416 \text{ m}^3$$

$$P \, V = mRT \qquad => \qquad P = \frac{mRT}{V}$$

$$\Rightarrow P = \frac{1.2 \text{ kg} \times 0.1889 \text{ kJ/kg K} \times (273.15 + 20) \text{ K}}{0.031416 \text{ m}^3} = \textbf{2115 kPa}$$

2.84

Ammonia in a piston/cylinder arrangement is at 700 kPa, 80°C. It is now cooled at constant pressure to saturated vapor (state 2) at which point the piston is locked with a pin. The cooling continues to −10°C (state 3). Show the processes 1 to 2 and 2 to 3 on both a *P–v* and *T–v* diagram.

Solution:

State 1: T, P   from table B.2.2   this is superheated vapor.

State 2: T, x   from table B.2.1

State 3: T, v   two-phase
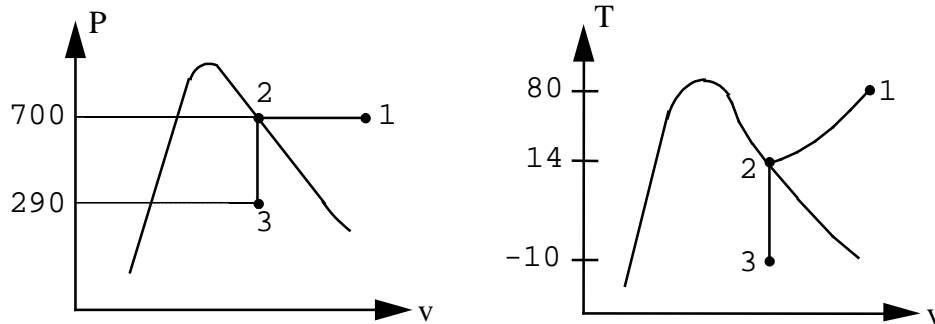
Compressibility Factor

2.85

Find the compressibility factor (Z) for saturated vapor ammonia at 100 kPa and at 2000 kPa.

Table B.2.2: $v_1 = 1.1381 \ m^3/kg$, $T_1 = -33.6°C$, $P_1 = 100 \ kPa$

                      $v_2 = 0.06444 \ m^3/kg$, $T_2 = 49.37°C$, $P_2 = 2000 \ kPa$

Table A.5: $R = 0.4882 \ kJ/kg \ K$

Extended gas law: $Pv = ZRT$ so we can calculate Z from this

$$Z_1 = \frac{P_1 v_1}{RT_1} = \frac{100 \ kPa \times 1.1381 \ m^3/kg}{0.4882 \ kJ/kg\text{-}K \times (273.15 - 33.6) \ K} = 0.973$$

$$Z_2 = \frac{P_2 v_2}{RT_2} = \frac{2000 \ kPa \times 0.06444 \ m^3/kg}{0.4882 \ kJ/kg\text{-}K \times (273.15 + 49.37) \ K} = 0.8185$$

So state 1 is close to ideal gas and state 2 is not so close.
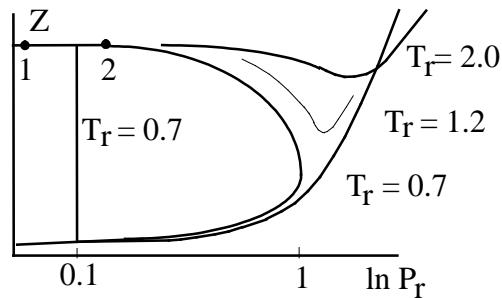
2.86

Find the compressibility for nitrogen at

a. 2000 kPa, 120 K ;   b. 2000 kPa, 300 K ;   c. 120 K, v = 0.005 m^3/kg

Solution:

Table B.6 has the properties for nitrogen.

a)   B.6.2: v = 0.01260 m^3/kg

$$Z = Pv/RT = \frac{2000 \text{ kPa} \times 0.01260 \text{ m}^3/\text{kg}}{0.2968 \text{ kJ/kg-K} \times 120 \text{ K}} = \mathbf{0.707}$$

b)   B.6.2: v = 0.04440 m^3/kg

$$Z = Pv/RT = \frac{2000 \text{ kPa} \times 0.04440 \text{ m}^3/\text{kg}}{0.2968 \text{ kJ/kg-K} \times 300 \text{ K}} = \mathbf{0.997}$$

c)   B.6.1: $v_f < v < v_g$ so this is a two-phase state.

$$Z = Pv/RT = \frac{2000 \text{ kPa} \times 0.005 \text{ m}^3/\text{kg}}{0.2968 \text{ kJ/kg-K} \times 120 \text{ K}} = \mathbf{0.28}$$

The liquid in this state is incompressible with a low volume and the vapor is very close to the critical point. If you calculate a quality it is x = 0.507. The compressibility for the saturated vapor alone is 0.44.

2.87

Find the compressibility for carbon dioxide at 60°C and 10 MPa using Fig. D.1

Solution:

Table A.2   CO2: T_c = 304.1 K P_c = 7.38 MPa

T_r = T/T_c = 333/304.1 = 1.095

P_r = P/P_c = 10/7.38 = 1.355

From Figure D.1:   **Z ≈ 0.45**

Compare with table B.3.2:   v = 0.00345 m^3/kg

$$Z = Pv/RT = \frac{10\ 000\ kPa \times 0.00345\ m^3/kg}{0.1889\ kJ/kg\text{-}K \times 333\ K} = 0.55$$
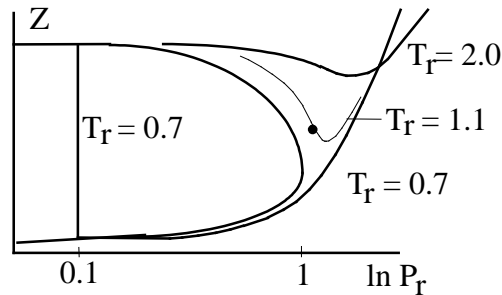
2.88

What is the percent error in specific volume if the ideal gas model is used to represent the behavior of superheated ammonia at 40°C, 500 kPa? What if the generalized compressibility chart, Fig. D.1, is used instead?

Solution:

NH_3 $T = 40°C = 313.15$ K, $T_c = 405.5$ K, $P_c = 11.35$ MPa from Table A.1

Table B.2.2: $v = \textbf{0.2923 m}^3\textbf{/kg}$

Ideal gas: $v = \dfrac{RT}{P} = \dfrac{0.48819 \text{ kJ/kgK} \times 313 \text{ K}}{500 \text{ kPa}} = \textbf{0.3056 m}^3\textbf{/kg} \Rightarrow \textbf{4.5\% error}$

Figure D.1: $T_r = \dfrac{313.15}{405.5} = 0.772,$ $P_r = \dfrac{0.5}{11.35} = 0.044$ $\Rightarrow Z = \textbf{0.97}$

$v = \dfrac{ZRT}{P} = \textbf{0.2964 m}^3\textbf{/kg}$ $\Rightarrow$ **1.4% error**

2.89

A cylinder fitted with a frictionless piston contains butane at 25°C, 500 kPa. Can the butane reasonably be assumed to behave as an ideal gas at this state ?

Solution

Butane 25°C, 500 kPa,   Table A.2: $T_c = 425$ K; $P_c = 3.8$ MPa

$$T_r = \frac{25 + 273}{425} = 0.701; \qquad P_r = \frac{0.5}{3.8} = 0.13$$

Look at generalized chart in Figure D.1

Actual $P_r > P_{r, \, sat} = 0.1$ =>   **liquid!! not a gas**

The pressure should be less than 380 kPa to have a gas at that T.

2.90

Estimate the saturation pressure of chlorine at 300 K.

Solution:
We do not have a table in the B section for Chlorine so we must use the generalized chart.

Table A.2: $P_c = 7.98$ MPa, $T_c = 416.9$ K

$T_r = T/T_c = 300 / 416.9 = 0.7196$

Figure D.1: $P_{r\ sat} = 0.13$ (same estimation from Table D.4)

$P = P_c\ P_{r\ sat} = 7.98 \times 0.13 = $ **1.04 MPa**

If you use the CATT3 program then you will find $P_{r\ sat} = 0.122$ and $P = 973$ kPa

2.91

A bottle with a volume of 0.1 m^3 contains butane with a quality of 75% and a temperature of 300 K. Estimate the total butane mass in the bottle using the generalized compressibility chart.

Solution:

We need to find the property v the mass is: m = V/v

so find v given T_1 and x   as : $v = v_f + x\ v_{fg}$

Table A.2:   Butane T_c = 425.2 K P_c = 3.8 MPa = 3800 kPa

T_r = 300/425.2 = 0.705   =>

From Fig. D.1 or table D.4: $Z_f \approx 0.02$; $Z_g \approx 0.9$; $P_{r\ sat}$ = 0.1
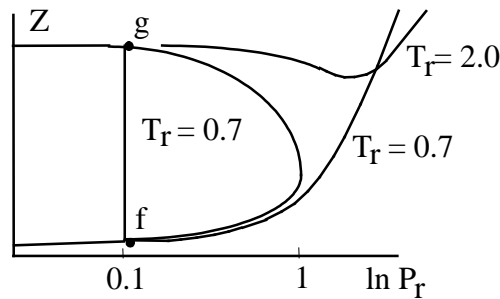
P = P_{sat} = $P_{r\ sat} \times P_c$ = 0.1× 3.80 MPa ×1000 kPa/MPa = 380 kPa

v_f = Z_fRT/P = 0.02 × 0.14304 kJ/kgK × 300 K/380 kPa = 0.00226 m^3/kg

v_g = Z_gRT/P = 0.9 × 0.14304 kJ/kgK × 300 K/380 kPa = 0.1016 m^3/kg

v = 0.00226 + 0.75 × (0.1016 – 0.00226) = 0.076765 m^3/kg

m $= \dfrac{V}{v} = \dfrac{0.1}{0.076765} =$ **1.303 kg**

2.92

Find the volume of 2 kg of ethylene at 270 K, 2500 kPa using Z from Fig. D.1

Ethylene Table A.2: $T_c = 282.4$ K, $P_c = 5.04$ MPa
Table A.5: $R = 0.2964$ kJ/kg K

The reduced temperature and pressure are:

$$T_r = \frac{T}{T_c} = \frac{270}{282.4} = 0.956, \quad P_r = \frac{P}{P_c} = \frac{2.5}{5.04} = 0.496$$

Enter the chart with these coordinates and read: $Z = 0.76$

$$V = \frac{mZRT}{P} = \frac{2 \text{ kg} \times 0.76 \times 0.2964 \text{ kJ/kg-K} \times 270 \text{ K}}{2500 \text{ kPa}} = \mathbf{0.0487 \ m^3}$$
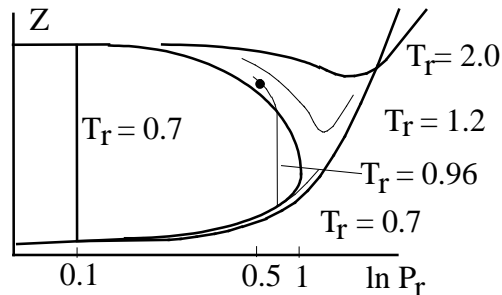
2.93

For $T_r = 0.7$, what is the ratio v_g/v_f using Fig. D.1 compared to Table. D.3

For the saturated states we can use Fig. D.1 with the estimates
$$Z_f = 0.02, \qquad Z_g = 0.9$$

so

$$v_g/v_f = (ZRT/P)_g / (ZRT/P)_f = Z_g/Z_f = \frac{0.02}{0.9} = \mathbf{0.0222}$$

Table D.3 list the entries more accurately than we can read the figure
$$Z_f = 0.017, \qquad Z_g = 0.897$$

so

$$v_g/v_f = (ZRT/P)_g / (ZRT/P)_f = Z_g/Z_f = \frac{0.017}{0.897} = \mathbf{0.0189}$$
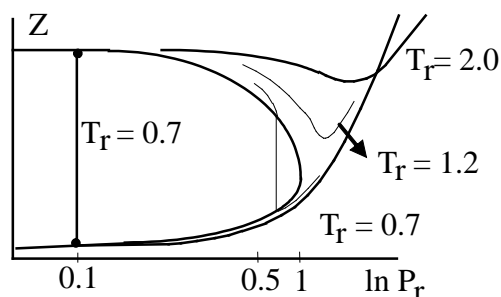
2.94

Argon is kept in a rigid 5 m^3 tank at $-30°C$, 3 MPa. Determine the mass using the compressibility factor. What is the error (%) if the ideal gas model is used?

Solution:

No Argon table, so we use generalized chart Fig. D.1

$T_r = 243.15/150.8 = 1.612$, $P_r = 3000/4870 = 0.616$ $=>$ $Z \cong 0.96$

$$m = \frac{PV}{ZRT} = \frac{3000 \text{ kPa} \times 5 \text{ m}^3}{0.96 \times 0.2081 \text{ kJ/kgK} \times 243.2 \text{ K}} = \textbf{308.75 kg}$$

Ideal gas $Z = 1$

$$m = \frac{PV}{RT} = 296.4 \text{ kg} \qquad \textbf{4\% error}$$

2.95

Refrigerant R-32 is at -10 $^{\circ}$C with a quality of 15%. Find the pressure and specific volume.

Solution:

For R-32 there is no section B table printed. We will use compressibility chart.

From Table A.2: $T_c = 351.3$ K ; $P_c = 5.78$ MPa ;

From Table A.5:   R = 0.1598 kJ/kg K

$T_r = T/T_c = 263/351.3 = 0.749$

From Table D.4 or Figure D.1, $Z_f \approx 0.029$; $Z_g \approx 0.86$; $P_{r\,sat} \approx 0.16$

$P = P_{r\,sat} P_c = 0.16 \times 5780 = \textbf{925 kPa}$

$v = v_f + x\,v_{fg} = (Z_f + x \times Z_{fg})\,RT/P$

$= [0.029 + 0.15 \times (0.86 - 0.029)] \times 0.1598 \text{ kJ/kg-K} \times 263 \text{ K}/ 925 \text{ kPa}$

$= \textbf{0.007 m}^{\textbf{3}}\textbf{/kg}$

2.96

To plan a commercial refrigeration system using R-123 we would like to know how much more volume saturated vapor R-123 occupies per kg at -30 $^{\circ}$C compared to the saturated liquid state.

Solution:

For R-123 there is no section B table printed. We will use compressibility chart.

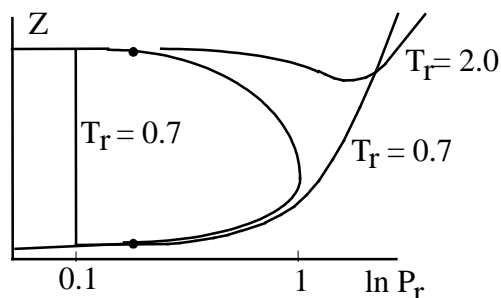   From Table A.2 $T_c = 456.9$ K ; $P_c = 3.66$ MPa ;   M = 152.93

   $T_r = T/T_c = 243/456.9 = 0.53$

   $R = \bar{R}/M = 8.31451$ kJ/kmol-K / 152.93 kg/kmol = 0.0544 kJ/kgK

The value of T_r is below the range in Fig. D.1 so use the table D.4

   Table D.4, $Z_g = 0.979$ $Z_f = 0.00222$

                  $Z_{fg} = 0.979 - 0.0022 = 0.9768;$ $P_r = P_{r\ sat} = 0.0116$

   $P = P_r \times P_c = 42.5$ kPa

   $v_{fg} = Z_{fg}\ RT/P = 0.9768 \times 0.0544$ kJ/kgK $\times 243$ K / 42.5 kPa

       $= \textbf{0.304 m}^\textbf{3}\textbf{/kg}$

Comment: If you check with the software the solution is off by a factor of 6. The linear interpolation is poor and so is the approximation for $P_{r\ sat}$ so the real saturation pressure should be 6.75 kPa. Also the very small value of Z_f is inaccurate by itself, minute changes in the curve gives large relative variations.

2.97

A new refrigerant R-125 is stored as a liquid at -20 °C with a small amount of vapor. For a total of 1.5 kg R-125 find the pressure and the volume.

Solution:

As there is no section B table use compressibility chart.

Table A.2:   R-125 $T_c = 339.2$ K $P_c = 3.62$ MPa

$T_r = T / T_c = 253.15 / 339.2 = 0.746$

We can read from Figure D.1 or a little more accurately interpolate from table D.4 entries:

$P_{r\ sat} = 0.16 ;\ \ Z_g = 0.86 ;\ \ \ \ Z_f = 0.029$

$P = P_{r\ sat}\ P_c = 0.16 \times 3620$ kPa = **579 kPa**

$V_{liq} = Z_f\ m_{liq}\ RT/P$

$\quad = 0.029 \times 1.5$ kg $\times 0.06927$ kJ/kgK $\times 253.15$ K/ 579 kPa

$\quad = $ **0.0013 m³**
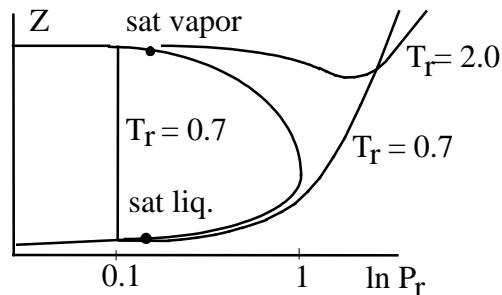
Equations of State

For these problems see appendix D for the equation of state (EOS) and chapter 12.

2.98

Determine the pressure of nitrogen at 160 K, v = 0.00291 m^3/kg using ideal gas, van der Waal Equation of State and the nitrogen table.

Nitrogen from table A.2: T_c = 126.2 K, P_c = 3390 kPa,

Ideal gas: $P = \dfrac{RT}{v} = \dfrac{0.2968 \times 160}{0.00291} \dfrac{\text{kJ/kg-K} \times \text{K}}{\text{m}^3\text{/kg}} =$ **16 319 kPa**

For **van der Waal equation of state** from Table D.1 we have

$$b = \frac{1}{8}\frac{RT_c}{P_c} = 0.125 \times \frac{0.2968 \times 126.2}{3390} = 0.001\ 381\ \text{m}^3\text{/kg,}$$

$$a = 27\ b^2\ P_c = 27 \times (0.001\ 381)^2 \times 3390 = 0.174\ 562\ \text{kPa (m}^3\text{/kg)}^2$$

The EOS is: $P = \dfrac{RT}{v-b} - \dfrac{a}{v^2} = \dfrac{0.2968 \times 160}{0.00291 \text{ - } 0.001\ 381} - \dfrac{0.174\ 562}{0.00291^2} =$ **10 444 kPa**

Table B.6.2:   P = **10 000 kPa**.

2.99

Determine the pressure of nitrogen at 160 K, v = 0.00291 m³/kg using Redlich-Kwong Equation of State and the nitrogen table.

Nitrogen from table A.2: T_c = 126.2 K, P_c = 3390 kPa,

$$T_r = T/T_c = 160/126.2 = 1.26783$$

For **Redlich-Kwong EOS** we have the parameters from Table D.1

$$b = 0.08664 \frac{RT_c}{P_c} = 0.08664 \times \frac{0.2968 \times 126.2}{3390} = 0.000\ 957\ 3\ \text{m}^3/\text{kg},$$

$$a = 0.42748\ T_r^{-1/2} \frac{R^2 T_c^2}{P_c} = 0.42748 \times \frac{0.2968^2 \times 126.2^2}{1.2678^{1/2} \times 3390} = 0.157\ 122\ \text{kPa}\ (\text{m}^3/\text{kg})^2$$

The equation is:

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

$$= \frac{0.2968 \times 160}{0.00291 - 0.000\ 9573} - \frac{0.157122}{0.00291^2 + 0.000\ 9573 \times 0.00291}$$

$$=\ \mathbf{10\ 357\ kPa}$$

Table B.6.2:   P = **10 000 kPa**.

2.100

Determine the pressure of nitrogen at 160 K, v = 0.00291 m^3/kg using Soave Equation of State and the nitrogen table.

Nitrogen from table A.2: T_c = 126.2 K, P_c = 3390 kPa,

$$T_r = T/T_c = 160/126.2 = 1.26783$$

For **Soave EOS** see Appendix D (very close to Redlich-Kwong)

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

where the parameters are from Table D.1 and D.4

$$\omega = 0.039$$

$$f = 0.48 + 1.574\omega - 0.176\omega^2 = 0.54112$$

$$a_o = 0.42748 \, [1 + f \, (1 - T_r^{1/2})]^2 = 0.371184$$

$$b = 0.08664 \, \frac{RT_c}{P_c} = 0.08664 \times \frac{0.2968 \times 126.2}{3390} = 0.000\ 957\ 3 \text{ m}^3/\text{kg},$$

$$a = 0.371184 \, \frac{R^2 T_c^2}{P_c} = 0.371184 \times \frac{0.2968^2 \times 126.2^2}{3390} = 0.153\ 616 \text{ kPa (m}^3/\text{kg})^2$$

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

$$= \frac{0.2968 \times 160}{0.00291 - 0.000\ 9573} - \frac{0.153\ 616}{0.00291^2 + 0.000\ 9573 \times 0.00291}$$

$$= \textbf{10 669 kPa}$$

Nitrogen Table B.6.2:   P = **10 000 kPa**.

2.101

Carbon dioxide at 60°C is pumped at a very high pressure 10 MPa into an oil well to reduce the oil viscosity for better oil flow. We want to find its specific volume from the CO_2 table, ideal gas and van der Waals equation of state by iteration.

Table B.3.2: $v = $ **0.00345 m³/kg**.

Ideal gas: $v = \dfrac{RT}{P} = \dfrac{0.1889 \times (60 + 273.15)}{10\ 000} \dfrac{\text{kJ/kg-K} \times \text{K}}{\text{kPa}} = $ **0.006 293 m³/kg**

Carbon dioxide from table A.2: $T_c = 304.1$ K, $P_c = 7380$ kPa,

For **van der Waal equation of state** from Table D.1 we have

$$b = \frac{1}{8}\frac{RT_c}{P_c} = 0.125 \times \frac{0.1889 \times 304.1}{7380} = 0.000\ 972\ 98 \text{ m}^3/\text{kg},$$

$$a = 27\ b^2\ P_c = 27 \times (0.000\ 972\ 98)^2 \times 7380 = 0.188\ 6375 \text{ kPa (m}^3/\text{kg})^2$$

The EOS is: $P = \dfrac{RT}{v - b} - \dfrac{a}{v^2}$

Since it is nonlinear in v we use trial and error starting with the Table entry.

$v = 0.00345:$ $P = \dfrac{0.1889 \times 333.15}{0.00345 - 0.000\ 972\ 98} - \dfrac{0.188\ 6375}{0.00345^2} = 9557.8$ kPa   low

$v = 0.003$ $P = \dfrac{0.1889 \times 333.15}{0.003 - 0.000\ 972\ 98} - \dfrac{0.188\ 6375}{0.003^2} = 10\ 086.8$ kPa   high

$v = 0.00307:$ $P = \dfrac{0.1889 \times 333.15}{0.00307 - 0.000\ 972\ 98} - \dfrac{0.188\ 6375}{0.00307^2} = 9995.4$ OK.

$v = $ **0.00307 m³/kg**

2.102

Solve the previous problem using the Redlich-Kwong equation of state. Notice this becomes trial and error.

Carbon dioxide from table A.2: $T_c = 304.1$ K, $P_c = 7380$ kPa,

$$T_r = T/T_c = 333.15/304.1 = 1.09553$$

For **Redlich-Kwong EOS** we have the parameters from Table D.1

$$b = 0.08664 \frac{RT_c}{P_c} = 0.08664 \times \frac{0.1889 \times 304.1}{7380} = 0.000\ 6744\ \text{m}^3/\text{kg},$$

$$a = 0.42748\ T_r^{-1/2} \frac{R^2 T_c^2}{P_c} = 0.42748 \times \frac{0.1889^2 \times 304.1^2}{1.09553^{1/2} \times 7380} = 0.18262\ \text{kPa (m}^3/\text{kg)}^2$$

The equation is:

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

$$10\ 000 = \frac{0.1889 \times 333.15}{v - 0.000\ 6744} - \frac{0.18262}{v^2 + 0.000\ 6744 \times v}$$

Trial and error on v (start guided by Table B.3.2):

$v = 0.0035$ m^3/kg ⇨	$P = 9772.8$ kPa	so v smaller
$v = 0.0033$ m^3/kg ⇨	$P = 10044.7$ kPa	so v larger
$v = 0.0034$ m^3/kg ⇨	$P = 9906.5$ kPa	

linear interpolation gives

$$v = \mathbf{0.00333\ m^3/kg} \quad ⇨ \quad P = 10002.7\ \text{kPa}\quad \text{OK.}$$

2.103

Solve Problem 2.101 using the Soave equation of state, $\omega = 0.239$. Notice this becomes trial and error.

Carbon dioxide from table A.2: $T_c = 304.1$ K, $P_c = 7380$ kPa,

$$T_r = T/T_c = 333.15/304.1 = 1.09553$$

For **Soave EOS** see Appendix D (very close to Redlich-Kwong)

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

where the parameters are from Table D.1 and D.4

$$\omega = 0.239$$

$$f = 0.48 + 1.574\omega - 0.176\omega^2 = 0.84613$$

$$a_o = 0.42748 \, [1 + f \, (1 - T_r^{1/2}) \,]^{\,2} = 0.394381$$

$$b = 0.08664 \, \frac{RT_c}{P_c} = 0.08664 \times \frac{0.1889 \times 304.1}{7380} = 0.000\,6744 \text{ m}^3/\text{kg,}$$

$$a = 0.394381 \, \frac{R^2 T_c^2}{P_c} = 0.394381 \times \frac{0.1889^2 \times 304.1^2}{7380} = 0.176\,342 \text{ kPa (m}^3/\text{kg})^2$$

The equation is:

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

$$10\,000 = \frac{0.1889 \times 333.15}{v \text{ - } 0.000\,6744} - \frac{0.176\,342}{v^2 + 0.000\,6744 \times v}$$

Trial and error on v (start guided by Table B.3.2):

$$v = 0.0035 \text{ m}^3/\text{kg} \quad \Rightarrow \qquad P = 10\,202 \text{ kPa} \quad \text{so v larger}$$

$$v = 0.0036 \text{ m}^3/\text{kg} \quad \Rightarrow \qquad P = 10\,051 \text{ kPa} \quad \text{so v close}$$

$$\mathbf{v = 0.00363 \text{ m}^3/\text{kg}} \quad \Rightarrow \qquad P = \ 10\,006 \text{ kPa}\ \ \text{OK}$$

2.104

A tank contains 8.35 kg methane in 0.1 m^3 at 250 K. Find the pressure using ideal gas, van der Waal EOS and the methane table.
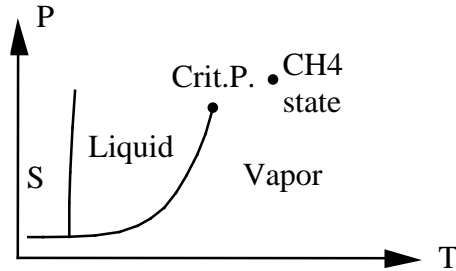
The state is given by (T = 250 K, v = V/m = 0.1/8.35 = 0.011976 m^3/kg)

Table A.2 or B.7.2:
   T_c = 190.4 K,
   P_c = 4600 kPa

$$T_r = \frac{T}{T_c} = \frac{250}{190.4} = 1.313$$

Ideal gas model: $P = \dfrac{RT}{v} = \dfrac{0.5183 \times 250}{0.011976} = 10\ 820$ kPa

For **van der Waal equation of state** from Table D.1 we have

$$b = \frac{1}{8}\frac{RT_c}{P_c} = 0.125 \times \frac{0.5183 \times 190.4}{4600} = 0.002\ 681\ 64\ \text{m}^3/\text{kg},$$

$$a = 27\ b^2\ P_c = 27 \times (0.002\ 681\ 64)^2 \times 4600 = 0.893\ 15\ \text{kPa (m}^3/\text{kg})^2$$

The EOS is: $P = \dfrac{RT}{v-b} - \dfrac{a}{v^2} = \dfrac{0.5183 \times 250}{0.011976\ \text{-}\ 0.002\ 681\ 64} - \dfrac{0.89315}{0.011976^2} = 7714$ kPa

Locating the state in **Table B.7.2:**   P = 8000 kPa, very close

2.105

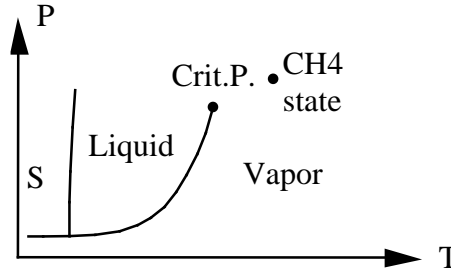Do the previous problem using the Redlich-Kwong equation of state.

The state is given by $(T = 250$ K, $v = V/m = 0.1/8.35 = 0.011976$ m^3/kg)

Table A.2 or B.7.2:
$\quad$ $T_c = 190.4$ K,
$\quad$ $P_c = 4600$ kPa

$$T_r = \frac{T}{T_c} = \frac{250}{190.4} = 1.313$$

Ideal gas model: $\quad P = \dfrac{RT}{v} = \dfrac{0.5183 \times 250}{0.011976} = 10\,820$ kPa

For **Redlich-Kwong equation of state** we have the parameters from Table D.1

$$b = 0.08664 \frac{RT_c}{P_c} = 0.08664 \times \frac{0.5183 \times 190.4}{4600} = 0.001\,858\,7 \text{ m}^3/\text{kg},$$

$$a = 0.42748 \, T_r^{-1/2} \frac{R^2 T_c^2}{P_c} = 0.42748 \times \frac{0.5183^2 \times 190.4^2}{1.313^{1/2} \times 4600} = 0.789809 \text{ kPa (m}^3/\text{kg)}^2$$

The equation is:

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

$$= \frac{0.5183 \times 250}{0.011976 - 0.0018587} - \frac{0.789809}{0.011976^2 + 0.0018587 \times 0.011976}$$

$$= \ 8040 \text{ kPa}$$

Locating the state in **Table B.7.2:** $\quad$ P = 8000 kPa, very close

2.106

Do Problem 2.104 using the Soave EOS.

A tank contains 8.35 kg methane in 0.1 m^3 at 250 K. Find the pressure using ideal gas, van der Waal EOS and the methane table.
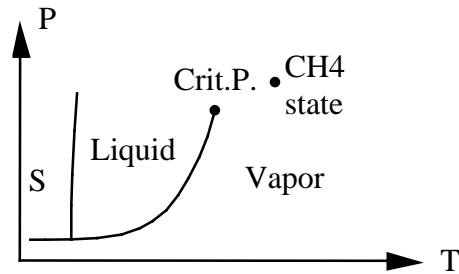
The state is given by (T = 250 K, v = V/m = 0.1/8.35 = 0.011976 m^3/kg)

Table A.2 or B.7.2:

T_c = 190.4 K,

P_c = 4600 kPa

$$T_r = \frac{T}{T_c} = \frac{250}{190.4} = 1.313$$

Ideal gas model: $P = \dfrac{RT}{v} = \dfrac{0.5183 \times 250}{0.011976} = 10\ 820$ kPa

For **Soave EOS** we have the parameters from Table D.1 and D.4

$$\omega = 0.011$$

$$f = 0.48 + 1.574\omega - 0.176\omega^2 = 0.49729$$

$$a_o = 0.42748\ [1 + f\ (1 - T_r^{1/2})\ ]^2 = 0.367714$$

$$b = 0.08664\ \frac{RT_c}{P_c} = 0.08664 \times \frac{0.5183 \times 190.4}{4600} = 0.001\ 8587\ m^3/kg,$$

$$a = 0.367714\ \frac{R^2T_c^2}{P_c} = 0.367714 \times \frac{0.5183^2 \times 190.4^2}{4600} = 0.778\ 482\ kPa\ (m^3/kg)^2$$

The equation is:

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

$$= \frac{0.5183 \times 250}{0.011976 - 0.001\ 8587} - \frac{0.778\ 482}{0.011976^2 + 0.0018587 \times 0.011976}$$

$$= \textbf{8108.7 kPa}$$

Locating the state in **Table B.7.2:**   P = 8000 kPa

Review Problems

2.107

Determine the quality (if saturated) or temperature (if superheated) of the following substances at the given two states:

Solution:

a) Water, H_2O, use Table B.1.1 or B.1.2

1) 120°C, 1 m³/kg $v > v_g$ superheated vapor, **T = 120 °C**

2) 10 MPa, 0.01 m³/kg   => two-phase $v < v_g$

$x = (0.01 - 0.001452) / 0.01657 = \textbf{0.516}$

b) Nitrogen, N_2, table B.6
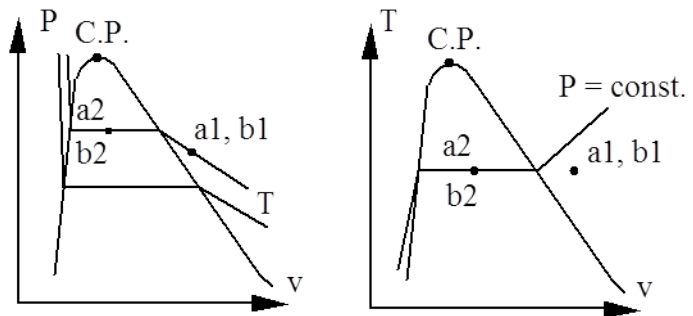
1) 1 MPa, 0.03 m³/kg => superheated vapor since $v > v_g$

Interpolate between sat. vapor and superheated vapor B.6.2:

$$T \cong 103.73 + (120\text{-}103.73) \times \frac{0.03-0.02416}{0.03117-0.02416} = \textbf{117 K}$$

2) 100 K, 0.03 m³/kg => sat. liquid + vapor as two-phase $v < v_g$

$v = 0.03 = 0.001452 + x \times 0.029764 \Rightarrow \textbf{x = 0.959}$

States shown are placed relative to the two-phase region, not to each other.

2.108

Give the phase and the missing properties of P, T, v and x.

Solution:

a. R-410A $T = 10°C$ $v = 0.01 \text{ m}^3/\text{kg}$

Table B.4.1 $v < v_g = 0.02383 \text{ m}^3/\text{kg}$

 sat. liquid + vapor. $P = P_{sat} = 1085.7 \text{ kPa}$,

$x = (v - v_f)/v_{fg} = (0.01 - 0.000886)/0.02295 = 0.2713$

b. H_2O $T = 350°C$ $v = 0.2 \text{ m}^3/\text{kg}$

Table B.1.1 at given T: $v > v_g = 0.00881 \text{ m}^3/\text{kg}$

sup. vapor $P \cong 1.40 \text{ MPa}$, $x = \text{undefined}$

c. R-410A $T = -5 °C$ $P = 600 \text{ kPa}$

sup. vapor $(P < P_g = 678,9 \text{ kPa at } -5°C)$

Table B.4.2:

$v = 0.04351 \text{ m}^3/\text{kg at } -8.67°C$

$v = 0.04595 \text{ m}^3/\text{kg at } 0°C$

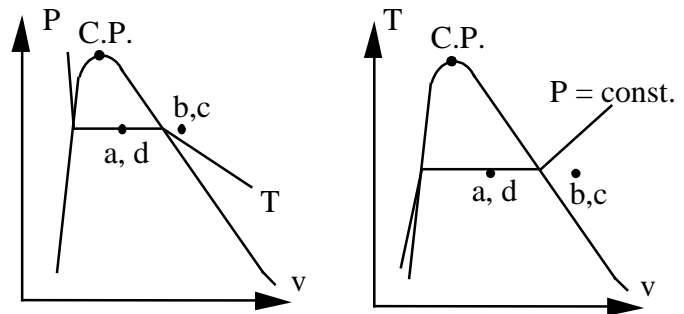   => $v = 0.04454 \text{ m}^3/\text{kg at } -5°C$

d. R-134a $P = 294 \text{ kPa}$, $v = 0.05 \text{ m}^3/\text{kg}$

Table B.5.1: $v < v_g = 0.06919 \text{ m}^3/\text{kg}$

two-phase $T = T_{sat} = 0°C$

$x = (v - v_f)/v_{fg} = (0.05 - 0.000773)/0.06842 = 0.7195$

States shown are placed relative to the two-phase region, not to each other.

2.109

Find the phase, quality x if applicable and the missing property P or T.

Solution:

a. H_2O $T = 120°C$ $v = 0.5$ m³/kg

Table B.1.1 at given T: $v < v_g = 0.89186$

sat. liq. + vap. $P = P_{sat} = $ **198.5 kPa,**

$x = (v - v_f)/v_{fg} = (0.5 - 0.00106)/0.8908 = $ **0.56**

b. H_2O $P = 100$ kPa $v = 1.8$ m³/kg

Table B.1.2 at given P: $v > v_g = 1.694$

sup. vap., interpolate in Table B.1.3

$$T = \frac{1.8 - 1.694}{1.93636 - 1.694}(150 - 99.62) + 99.62 = \textbf{121.65 °C}$$

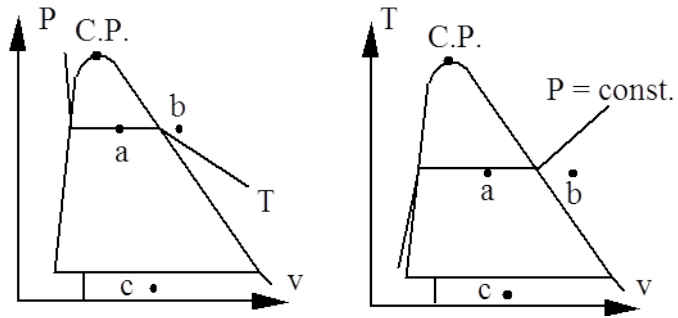c. H_2O $T = 263$ K $v = 0.2$ m³/kg

Table B.1.5 at given T = -10 °C: $v < v_g = 466.757$

sat. solid + vap., $P = P_{sat} = $ **0.26 kPa,**

$x = (v - v_i)/v_{ig} = (200 - 0.001)/466.756 = $ **0.4285**

States shown are
placed relative to the
two-phase region, not
to each other.

2.110

Find the phase, quality x if applicable and the missing property P or T.

Solution:

    a. NH_3 $P = 800$ kPa $v = 0.2$ m^3/kg;

                 Superheated Vapor ($v > v_g$ at 800 kPa)

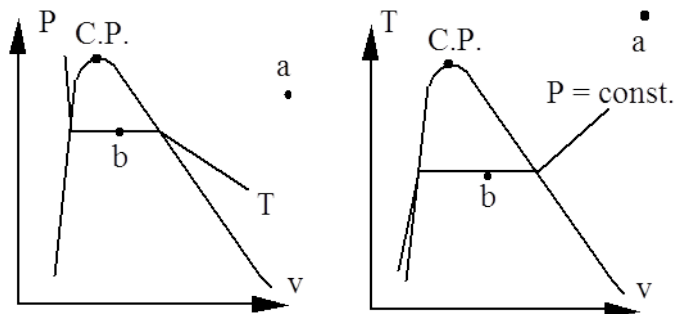   Table B 2.2 interpolate between 70°C and 80°C

                 T = **71.4°C**

    b. NH_3 $T = 20$°C $v = 0.1$ m^3/kg

                 Table B.2.1 at given T: $v < v_g = 0.14922$

                 sat. liq. + vap. , $P = P_{sat} = $ **857.5 kPa,**

                 $x = (v - v_f)/v_{fg} = (0.1 - 0.00164)/0.14758 = $ **0.666**

2.111

Give the phase and the missing properties of P, T, v and x. These may be a little more difficult if the appendix tables are used instead of the software.

a) R-410A at $T = 10°C$, $v = 0.02$ m^3/kg: Table B.4.1 $v > v_g$ at 10°C

=> **sup. vap.**   Table B.4.2 interpolate between sat. and sup. both at 10°C

$P = 680.7 + (600 - 680.7) \dfrac{0.036\text{-}0.03471}{0.04018\text{-}0.03471} = \textbf{661.7 kPa}$

b) H$_2$O $v = 0.2$ m^3/kg , $x = 0.5$: Table B.1.1

sat. liq. + vap. $v = (1\text{-}x)\, v_f + x\, v_g$ => $v_f + v_g = 0.4$ m^3/kg

since v_f is so small we find it approximately where $v_g = 0.4$ m^3/kg.

$v_f + v_g = 0.39387$ at 150°C, $v_f + v_g = 0.4474$ at 145°C.

An interpolation gives   T $\cong$ **149.4°C,**   P $\cong$ **468.2 kPa**

c) H$_2$O $T = 60°C$, $v = 0.001016$ m^3/kg: Table B.1.1 $v < v_f = 0.001017$

=> **compr. liq.**   see Table B.1.4

$v = 0.001015$ at 5 MPa so $P \cong 0.5(5000 + 19.9) = \textbf{2.51 MPa}$

d) NH$_3$ $T = 30°C$, $P = 60$ kPa : Table B.2.1 $P < P_{sat}$

=> **sup. vapor**   interpolate in Table B.2.2   (50 kPa to 100 kPa)

$v = 2.9458 + (1.4657 - 2.9458) \dfrac{60 - 50}{100 - 50} = \textbf{2.65 m}^3\textbf{/kg}$

v is not linearly proportional to P (more like 1/P) so the computer table gives a more accurate value of 2.45 m^3/kg

e) R-134a $v = 0.005$ m^3/kg , $x = 0.5$:   **sat. liq. + vap.**   Table B.5.1

$v = (1\text{-}x)\, v_f + x\, v_g$ => $v_f + v_g = 0.01$ m^3/kg

$v_f + v_g = 0.010946$ at 65°C, $v_f + v_g = 0.009665$ at 70°C.

An interpolation gives: T $\cong$ **68.7°C**, P = **2.06 MPa**

States shown are placed relative to the two-phase region, not to each other.
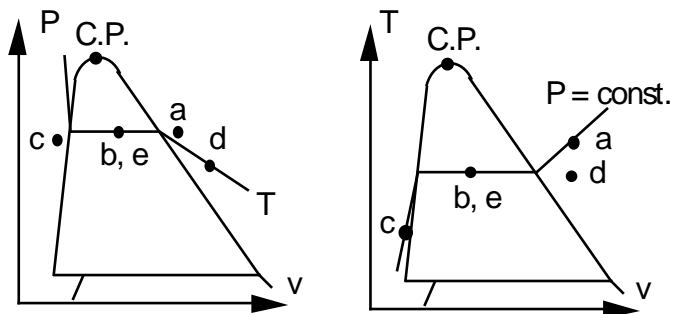
2.112

Refrigerant-410a in a piston/cylinder arrangement is initially at 50°C, $x = 1$. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 100 kPa. Find the final temperature and specific volume.
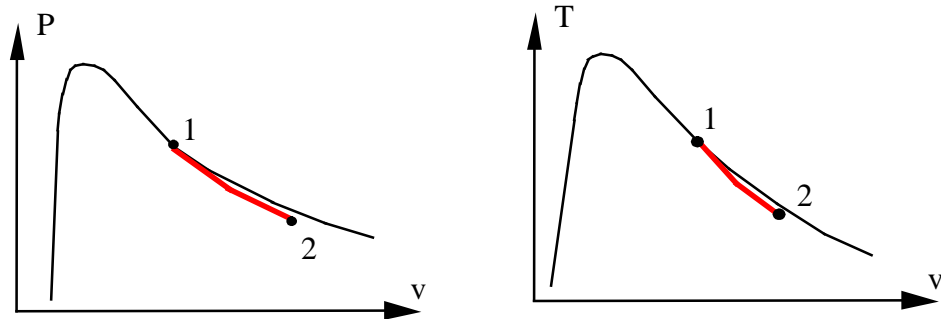
Solution:

State 1: 50°C, x = 1   Table B.4.1: $P_1 = 3065.2$ kPa, $v_1 = 0.00707$ m³/kg

Process: $Pv = C = P_1v_1$;   => $P_2 = C/v_2 = P_1v_1/v_2$

State 2: 100 kPa and $v_2 = v_1P_1/P_2 = $ **0.2167 m³/kg**

    $v_2 < v_g$ at 100 kPa, $T_2 \cong$ **-51.65°C** from Table B.4.2

Notice T is **not** constant

The first part of the process may be in the sup. vapor region.

2.113

Consider two tanks, A and B, connected by a valve, as shown in Fig. P2.113. Each has a volume of 200 L and tank A has R-410A at 25°C, 10% liquid and 90% vapor by volume, while tank B is evacuated. The valve is now opened and saturated vapor flows from A to B until the pressure in B has reached that in A, at which point the valve is closed. This process occurs slowly such that all temperatures stay at 25°C throughout the process. How much has the quality changed in tank A during the process?

Solution:
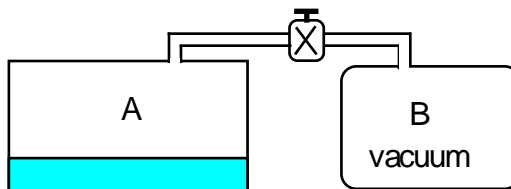
State A1: Table B.4.1 $v_f = 0.000944$ m^3/kg, $v_g = 0.01514$ m^3/kg

$$m_{A1} = \frac{V_{liq1}}{v_{f\,25°C}} + \frac{V_{vap1}}{v_{g\,25°C}} = \frac{0.1 \times 0.2}{0.000944} + \frac{0.9 \times 0.2}{0.01514}$$

$$= 21.186 + 11.889 = 33.075 \text{ kg}$$

$$x_{A1} = \frac{11.889}{33.075} = 0.3594 \; ;$$

State B2: Assume A still two-phase so saturated P for given T

$$m_{B2} = \frac{V_B}{v_{g\,25°C}} = \frac{0.2}{0.01514} = 13.210 \text{ kg}$$
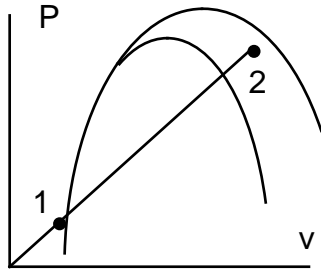
State A2: mass left is $m_{A2} = 33.075 - 13.210 = 19.865$ kg

$$v_{A2} = \frac{0.2}{19.865} = 0.010068 = 0.000944 + x_{A2} \times 0.01420$$

$$x_{A2} = 0.6425 \qquad\qquad \Delta x = \mathbf{0.283}$$

2.114

Water in a piston/cylinder is at 90°C, 100 kPa, and the piston loading is such that pressure is proportional to volume, $P = CV$. Heat is now added until the temperature reaches 200°C. Find the final pressure and also the quality if in the two-phase region.

Solution:

Final state: 200°C , on process line $P = CV$

State 1:   Table B.1.1: $v_1 = 0.001036 \text{ m}^3/\text{kg}$

$P_2 = P_1 v_2 / v_1$ from process equation

Check state 2 in Table B.1.1

$v_g(T_2) = 0.12736; \quad P_g(T_2) = 1.5538 \text{ MPa}$

If $v_2 = v_g(T_2) \quad \Rightarrow \quad P_2 = 12.3 \text{ MPa} > P_g$ not OK

If sat. $P_2 = P_g(T_2) = 1553.8 \text{ kPa} \quad \Rightarrow \quad v_2 = 0.0161 \text{ m}^3\text{kg} < v_g$ sat. OK,

$P_2 = 1553.8 \text{ kPa}$, $x_2 = (0.0161 - 0.001156) / 0.1262 = \textbf{0.118}$
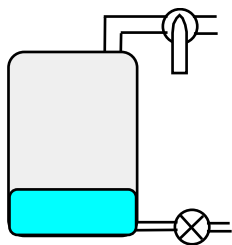
2.115

A tank contains 2 kg of nitrogen at 100 K with a quality of 50%. Through a volume flowmeter and valve, 0.5 kg is now removed while the temperature remains constant. Find the final state inside the tank and the volume of nitrogen removed if the valve/meter is located at

  a.   The top of the tank
  b.   The bottom of the tank

Solution

Table B.6.1:

$v_1 = 0.001452 + x_1 \times 0.029764 = 0.016334$ m^3/kg

$V_{tank} = m_1 v_1 = 0.0327$ m^3

$m_2 = m_1 - 0.5 = 1.5$ kg

$v_2 = V_{tank}/m_2 = 0.0218 < v_g(T)$

$x_2 = \dfrac{0.0218 - 0.001452}{0.031216 - 0.001452} = \mathbf{0.6836}$

Top: flow out is sat. vap. $v_g = 0.031216$ m^3/kg, $V_{out} = m_{out} v_g = \mathbf{0.0156}$ **m**^{3}

Bottom: flow out is sat. liq. $v_f = 0.001452$ $V_{out} = m_{out} v_f = \mathbf{0.000726}$ **m**^{3}

2.116

A spring-loaded piston/cylinder contains water at 500°C, 3 MPa. The setup is such that pressure is proportional to volume, $P = CV$. It is now cooled until the water becomes saturated vapor. Sketch the *P-v* diagram and find the final pressure.
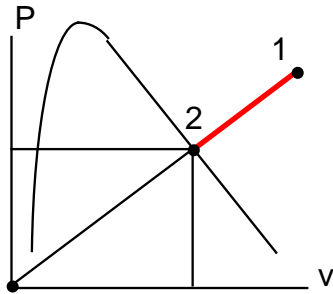
Solution:

State 1:   Table B.1.3: $v_1 = 0.11619$ m^3/kg

Process: m is constant and $P = C_0V = C_0 m\, v = C\, v$

$$P = Cv \implies C = P_1/v_1 = 3000/0.11619 = 25820 \text{ kPa kg/m}^3$$

State 2: $x_2 = 1$ & $P_2 = Cv_2$ (on process line)

Trial & error on T_{2sat} or P_{2sat}:

Here from B.1.2:

at 2 MPa $v_g = 0.09963 \implies C = 20074$ (low)

2.5 MPa $v_g = 0.07998 \implies C = 31258$ (high)

2.25 MPa $v_g = 0.08875 \implies C = 25352$ (low)

Interpolate to get the right C $\implies$ **$P_2 = 2270$ kPa**

2.117

A container with liquid nitrogen at 100 K has a cross sectional area of 0.5 m^2. Due to heat transfer, some of the liquid evaporates and in one hour the liquid level drops 30 mm. The vapor leaving the container passes through a valve and a heater and exits at 500 kPa, 260 K. Calculate the volume rate of flow of nitrogen gas exiting the heater.

Solution:

Properties from table B.6.1 for volume change, exit flow from table B.6.2:

$$\Delta V = A \times \Delta h = 0.5 \times 0.03 = 0.015 \text{ m}^3$$

$$\Delta m_{liq} = -\Delta V/v_f \qquad = -0.015/0.001452 = -10.3306 \text{ kg}$$

$$\Delta m_{vap} = \Delta V/v_g \qquad = 0.015/0.0312 = 0.4808 \text{ kg}$$

$$m_{out} = 10.3306 - 0.4808 = 9.85 \text{ kg}$$

$$v_{exit} = 0.15385 \text{ m}^3/\text{kg}$$

$$\dot{V} = \dot{m}v_{exit} = (9.85 / 1 \text{ } h) \times 0.15385 \text{ m}^3/\text{kg}$$

$$= 1.5015 \text{ m}^3/\text{h} = \mathbf{0.02526 \text{ m}^3/min}$$

2.118

For a certain experiment, R-410A vapor is contained in a sealed glass tube at 20°C. It is desired to know the pressure at this condition, but there is no means of measuring it, since the tube is sealed. However, if the tube is cooled to –20°C small droplets of liquid are observed on the glass walls. What is the initial pressure?

Solution:

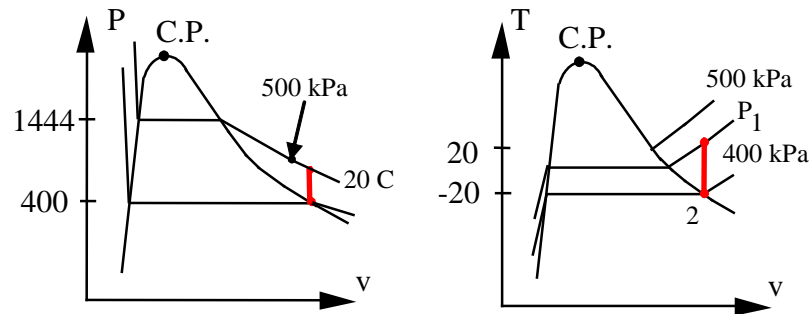Control volume: R-410A fixed volume (V) & mass (m) at 20°C

Process: cool to -20°C at constant v, so we assume saturated vapor

State 2: $v_2 = v_{g\ at\ -20°C} = 0.06480\ m^3/kg$

State 1: 20°C, $v_1 = v_2 = 0.06480\ m^3/kg$

interpolate between 400 and 500 kPa in Table B.4.2

$=>$ **$P_1 = 485\ kPa$**

2.119

A cylinder/piston arrangement contains water at 105°C, 85% quality with a volume of 1 L. The system is heated, causing the piston to rise and encounter a linear spring as shown in Fig. P2.119. At this point the volume is 1.5 L, piston diameter is 150 mm, and the spring constant is 100 N/mm. The heating continues, so the piston compresses the spring. What is the cylinder temperature when the pressure reaches 200 kPa?

Solution:

$P_1 = 120.8$ kPa, $v_1 = v_f + x\, v_{fg} = 0.001047 + 0.85*1.41831 = 1.20661$

$m = V_1 / v_1 = \dfrac{0.001}{1.20661} = 8.288 \times 10^{-4}$ kg

$v_2 = v_1\, (V_2 / V_1) = 1.20661 \times 1.5 = 1.8099$

& $P = P_1 = 120.8$ kPa   ($T_2 = 203.5$°C)

$P_3 = P_2 + (k_s/A_p{}^2)\, m(v_3 - v_2)$ linear spring

$A_p = (\pi/4) \times 0.15^2 = 0.01767$ m^2 ; $k_s = 100$ kN/m (matches P in kPa)

$200 = 120.8 + (100/0.01767^2) \times 8.288 \times 10^{-4}(v_3 - 1.8099)$

$200 = 120.8 + 265.446\ (v_3 - 1.8099)$ => $v_3 = 2.1083$ m^3/kg

$T_3 \cong 600 + 100 \times (2.1083 - 2.01297)/(2.2443 - 2.01297) \cong$ **641°C**
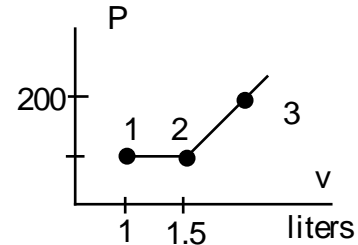
2.120

Determine the mass of methane gas stored in a 2 m^3 tank at –30°C, 2 MPa. Estimate the percent error in the mass determination if the ideal gas model is used.
Solution:

Table B.7

Methane Table B.7.1 at –30°C = 243.15 K > T_c = 190.6 K,   so superheated vapor in Table B.7.2. Linear interpolation between 225 and 250 K at 2 MPa.

$$\Rightarrow \ v \cong 0.05289 + \frac{243.15\text{-}225}{250\text{-}225} \times (0.06059 - 0.05289) = 0.05848 \ \text{m}^3/\text{kg}$$

$$m = V/v = 2/0.05848 = 34.2 \ \text{kg}$$

Ideal gas assumption

$$v = \frac{RT}{P} = \frac{0.51835 \times 243.15}{2000} = 0.06302 \ \text{m}^3/\text{kg}$$

$$m = \frac{V}{v} = \frac{2}{0.06302} = 31.74 \ \text{kg}$$

Error:

$$\Delta m = 2.46 \ \text{kg} \ ; \ \ \text{ideal gas } \textbf{7.2\% too small}$$

Comment: The compressibility of the methane Z = 0.93.

2.121

A cylinder containing ammonia is fitted with a piston restrained by an external force
that is proportional to cylinder volume squared. Initial conditions are 10°C, 90%
quality and a volume of 5 L. A valve on the cylinder is opened and additional
ammonia flows into the cylinder until the mass inside has doubled. If at this point the
pressure is 1.2 MPa, what is the final temperature?

Solution:

State 1 Table B.2.1: $v_1 = 0.0016 + 0.9(0.205525 - 0.0016) = 0.18513$ m^3/kg

$$P_1 = 615 \text{ kPa}; \quad V_1 = 5 \text{ L} = 0.005 \text{ m}^3$$

$$m_1 = V/v = 0.005/0.18513 = 0.027 \text{ kg}$$

State 2: $P_2 = 1.2$ MPa, Flow in so: $m_2 = 2 \ m_1 = 0.054$ kg

Process: Piston $F_{ext} = KV^2 = PA \quad => \quad P = CV^2 \quad => P_2 = P_1 \ (V_2/V_1)^2$

From the process equation we then get:

$$V_2 = V_1 \ (P_2/P_1)^{1/2} = 0.005 \ (\frac{1200}{615})^{1/2} = 0.006984 \text{ m}^3$$

$$v_2 = V/m = \frac{0.006984}{0.054} = 0.12934 \text{ m}^3/\text{kg}$$

At P_2, v_2: $T_2 = \mathbf{70.9°C}$

2.122

A cylinder has a thick piston initially held by a pin as shown in Fig. P2.122. The cylinder contains carbon dioxide at 200 kPa and ambient temperature of 290 K. The metal piston has a density of 8000 kg/m^3 and the atmospheric pressure is 101 kPa. The pin is now removed, allowing the piston to move and after a while the gas returns to ambient temperature. Is the piston against the stops?

Solution:

Force balance on piston determines equilibrium float pressure.

Piston $m_p = A_p \times l \times \rho$ $\qquad\qquad\qquad$ $\rho_{piston} = 8000$ kg/m^3

$$P_{ext\ on\ CO_2} = P_0 + \frac{m_p g}{A_p} = 101 + \frac{A_p \times 0.1 \times 9.807 \times 8000}{A_p \times 1000} = 108.8 \text{ kPa}$$

Pin released, as $P_1 > P_{ext}$ piston moves up, $T_2 = T_o$ & if piston at stops,

then $\quad V_2 = V_1 \times H_2/H_1 = V_1 \times 150 / 100$

Ideal gas with $T_2 = T_1$ then gives

$$\Rightarrow\ P_2 = P_1 \times V_1 / V_2 = 200 \times \frac{100}{150} = 133 \text{ kPa} > P_{ext}$$

$\Rightarrow$ **piston is at stops, and P$_2$ = 133 kPa**

2.123

What is the percent error in pressure if the ideal gas model is used to represent the behavior of superheated vapor R-410A at 60°C, 0.03470 m^3/kg? What if the generalized compressibility chart, Fig. D.1, is used instead (iterations needed)?

Solution:

Real gas behavior: P = 1000 kPa   from Table B.4.2

Ideal gas constant: $R = \bar{R}/M = 8.31451/72.585 = 0.1146$ kJ/kg K

P = RT/v = 0.1146 × (273.15 + 60) / 0.0347

= **1100 kPa   which is 10% too high**

Generalized chart Fig D.1 and critical properties from A.2:

$T_r = 333.2/(273.15 + 71.3) = 0.967;$ $P_c = 4901$ kPa

Assume P = 1000 kPa   => $P_r = 0.204$ => Z ≅ 0.92

v = ZRT/P = 0.92 × 0.1146 kJ/kg-K × 333.15 K /1000 kPa

= 0.03512 m^3/kg   too high

Assume P = 1050 kPa   => $P_r = 0.214$ => Z ≅ 0.915

v = ZRT/P = 0.915 × 0.1146 kJ/kg-K × 333.15 K / 1050 kPa

= 0.03327 m^3/kg   too low

$$P \cong 1000 + (1050 - 1000) \times \frac{0.03470 - 0.03512}{0.03327 - 0.03512} = \textbf{1011 kPa   1.1 \% high}$$

2.124

An initially deflated and flat balloon is connected by a valve to a 12 m³ storage tank containing helium gas at 2 MPa and ambient temperature, 20°C. The valve is opened and the balloon is inflated at constant pressure, P_O = 100 kPa, equal to ambient pressure, until it becomes spherical at D_1 = 1 m. If the balloon is larger than this, the balloon material is stretched giving a pressure inside as

$$P = P_0 + C\left(1 - \frac{D_1}{D}\right)\frac{D_1}{D}$$

The balloon is inflated to a final diameter of 4 m, at which point the pressure inside is 400 kPa. The temperature remains constant at 20°C. What is the maximum pressure inside the balloon at any time during this inflation process? What is the pressure inside the helium storage tank at this time?

Solution:

At the end of the process we have D = 4 m so we can get the constant C as

$$P = 400 = P_0 + C\,(\,1 - \frac{1}{4}\,)\frac{1}{4} = 100 + C \times 3/16 \quad \Rightarrow \quad C = 1600 \text{ kPa}$$

The pressure is: $P = 100 + 1600\,(\,1 - X^{-1})\,X^{-1}; \qquad X = D / D_1$

Differentiate to find max: $\dfrac{dP}{dD} = C\,(\,\text{-}\,X^{-2} + 2\,X^{-3}\,)\,/\,D_1 = 0$

$$\Rightarrow \; \text{-}\,X^{-2} + 2\,X^{-3} = 0 \;\Rightarrow\quad X = 2$$

at max P => D = $2D_1$ = 2 m; $V = \dfrac{\pi}{6}D^3 = 4.18 \text{ m}^3$

$$\text{Pmax} = 100 + 1600\,(\,1 - \frac{1}{2}\,)\,\frac{1}{2} = \textbf{500 kPa}$$

Helium is ideal gas A.5: $m = \dfrac{PV}{RT} = \dfrac{500 \times 4.189}{2.0771 \times 293.15} = 3.44 \text{ kg}$

$m_{TANK,\,1} = \dfrac{PV}{RT} = \dfrac{2000 \times 12}{2.0771 \times 293.15} = 39.416 \text{ kg}$

$m_{TANK,\,2} = 39.416 - 3.44 = 35.976 \text{ kg}$

$P_{T2} = m_{TANK,\,2}\,RT/V = (\,m_{TANK,\,1}\,/\;m_{TANK,\,2}\,) \times P_1 = \textbf{1825.5 kPa}$

2.125

A piston/cylinder arrangement, shown in Fig. P2.125, contains air at 250 kPa, 300°C. The 50-kg piston has a diameter of 0.1 m and initially pushes against the stops. The atmosphere is at 100 kPa and 20°C. The cylinder now cools as heat is transferred to the ambient.

a. At what temperature does the piston begin to move down?
b. How far has the piston dropped when the temperature reaches ambient?

Solution:

Piston $\quad A_p = \frac{\pi}{4} \times 0.1^2 = 0.00785 \text{ m}^2$

Balance forces when piston floats:

$$P_{float} = P_o + \frac{m_p g}{A_p} = 100 + \frac{50 \times 9.807}{0.00785 \times 1000}$$
$$= 162.5 \text{ kPa} = P_2 = P_3$$

To find temperature at 2 assume ideal gas:

$$T_2 = T_1 \times \frac{P_2}{P_1} = 573.15 \times \frac{162.5}{250} = \textbf{372.5 K}$$

b) Process 2 -> 3 is constant pressure as piston floats to $T_3 = T_O = 293.15$ K

$$V_2 = V_1 = A_p \times H = 0.00785 \times 0.25 = 0.00196 \text{ m}^3 = 1.96 \text{ L}$$

Ideal gas and $P_2 = P_3 \quad => \quad V_3 = V_2 \times \frac{T_3}{T_2} = 1.96 \times \frac{293.15}{372.5} = \textbf{1.54 L}$

$$\Delta H = (V_2 - V_3)/A = (1.96 - 1.54) \times 0.001/0.00785 = \textbf{0.053 m = 5.3 cm}$$
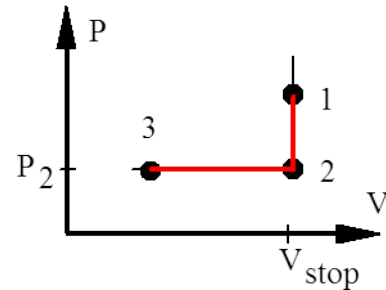
Linear Interpolation

2.126

Find the pressure and temperature for saturated vapor R-410A with v = 0.1 m^3/kg
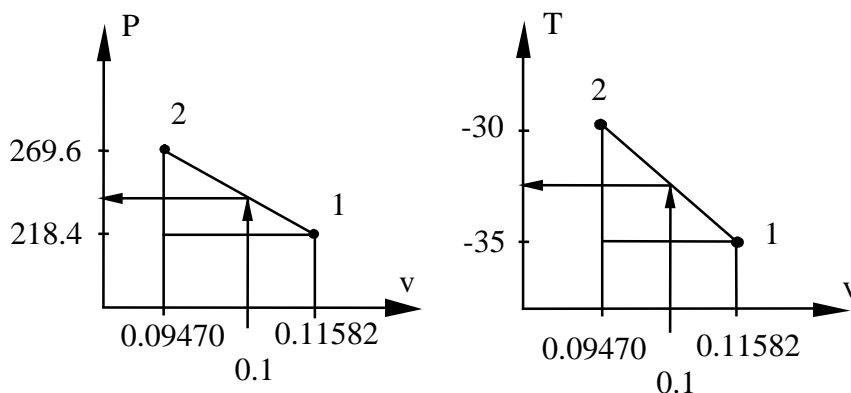
Solution:

Table B.4.1 Look at the saturated vapor column v_g and it is found between -35°C and -30°C. We must then do a linear interpolation between these values.

$$T = -35 + [-30 - (-35)]\frac{0.1 - 0.11582}{0.09470 - 0.11582}$$

$$= -35 + 5 \times 0.749 = \textbf{-31.3}^\circ\textbf{C}$$

$$P = 218.4 + (269.6 - 218.4) \times 0.749 = \textbf{256.7 kPa}$$

To understand the interpolation equation look at the smaller and larger triangles formed in the figure. The ratio of the side of the small triangle in v as (0.11582 - 0.1) to the side of the large triangle (0.11582 − 0.09470) is equal to 0.749. This fraction of the total $\Delta P = 269.6 - 218.4$ or $\Delta T = -30 - (-35)$ is added to the lower value to get the desired interpolated result.

2.127

Use a linear interpolation to estimate properties of ammonia to fill out the table below

	P [kPa]	T [$^\circ$C]	v [m^3/kg]	x
a)	550			0.75
b)	80	20		
c)		10	0.4	

Solution:

a)   Find the pressures in Table B.2.1 that brackets the given pressure.

$$T = 5 + (10 - 5)\frac{550 - 515.9}{615.2 - 515.9} = 5 + 5 \times 0.341 = \textbf{6.7 }^\circ\textbf{C}$$

$$v_f = 0.001583 + (0.0016 - 0.001583)\,0.341 = 0.001589 \text{ m}^3\text{/kg}$$

$$v_g = 0.24299 + (0.20541 - 0.24299)\,0.341 = 0.230175 \text{ m}^3\text{/kg}$$

$$v = v_f + xv_{fg} = 0.001589 + 0.75(0.230175 - 0.001589)$$

$$= \textbf{0.1729 m}^3\textbf{/kg}$$

b)   Interpolate between 50 and 100 kPa to get properties at 80 kPa

$$v = 2.8466 + (1.4153 - 2.8466)\frac{80 - 50}{100 - 50}$$

$$= 2.8466 + (-1.4313) \times 0.6 = \textbf{1.9878 m}^3\textbf{/kg}$$

x: Undefined

c)   Table B.2.1: $v > v_g$ so the state is superheated vapor.

Table B.2.2 locate state between 300 and 400 kPa.

$$P = 300 + (400 - 300)\frac{0.4 - 0.44251}{0.32701 - 0.44251}$$

$$= 300 + 100 \times 0.368 = \textbf{336.8 kPa}$$

x: Undefined

2.128

Use a linear interpolation to estimate Tsat at 900 kPa for nitrogen. Sketch by hand the curve Psat(T) by using a few table entries around 900 kPa from table B.6.1. Is your linear interpolation over or below the actual curve?

Solution:

The 900 kPa in Table B.6.1 is located between 100 and 105 K.

$$T = 100 + (105 - 100)\,\frac{900 - 779.2}{1084.6 - 779.2}$$
$$= 100 + 5 \times 0.3955 = \mathbf{102\ K}$$

The actual curve has a positive second derivative (it curves up) so T is slightly underestimated by use of the chord between the 100 K and the 105 K points, as the chord is above the curve.
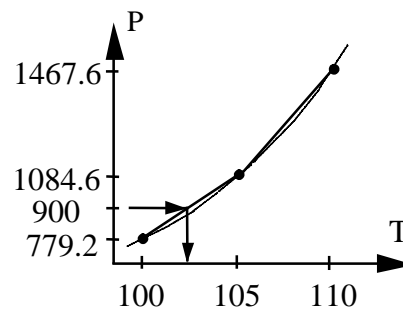
2.129

Use a double linear interpolation to find the pressure for superheated R-134a at 13°C with v = 0.3 m^3/kg.

Solution:

Table B.5.2: Superheated vapor

At 10°C, 0.3 m^3/kg

$$P = 50 + (100 - 50) \times \frac{0.3 - 0.45608}{0.22527 - 0.45608} = 83.8 \text{ kPa}$$

At 20°C, 0.3 m^3/kg

$$P = 50 + (100 - 50) \times \frac{0.3 - 0.47287}{0.23392 - 0.47287} = 86.2 \text{ kPa}$$

Interpolating to get 13°C between the 10°C and 20°C P's above,
$$P = 83.8 + (3/10) \times (86.2 - 83.8) = \textbf{84.5 kPa}$$

This could also be interpolated as following:

At 13°C, 50 kPa,   v = 0.45608 + (3/10) × 0.0168 = 0.4611 m^3/kg
At 13°C, 100 kPa,   v = 0.22527 + (3/10) × 0.0087 = 0.2279 m^3/kg

Interpolating at 0.3 m^3/kg.

$$P = 50 + (100 - 50) \times \frac{0.3 - 0.4611}{0.2279 - 0.4611} = \textbf{84.5 kPa}$$

2.130

Find the specific volume for CO_2 at $0\,^{O}C$ and 625 kPa.

Solution:

The state is superheated vapor in Table B.3.2 between 400 and 800 kPa.

$$v = 0.12552 + (0.06094 - 0.12552)\frac{625 - 400}{800 - 400}$$

$$= 0.12552 + (-0.06458) \times 0.5625 = \mathbf{0.0892\ m^3/kg}$$
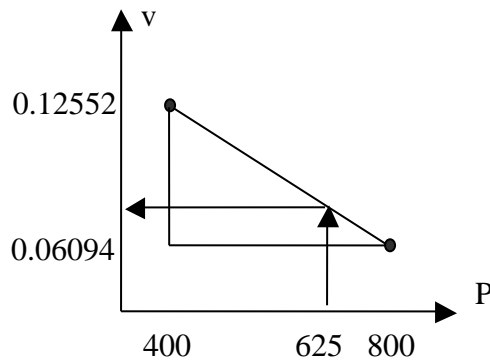
Computer Tables

2.131

Use the computer software to find the properties for water at the 4 states in Problem 2.35

Start the software, click the tab for water as the substance, and click the small calculator icon. Select the proper CASE for the given properties.

	CASE	RESULT
a)	1 (T, P)	Compressed liquid, x = undefined, $v = 0.001002$ m^3/kg
b)	5 (P, v)	Two-phase, T = 151.9°C, $x = 0.5321$
c)	1 (T, P)	Sup. vapor, x = undefined, $v = 0.143$ m^3/kg
d)	4 (T, x)	$P = P_{sat} = 8581$ kPa, $v = 0.01762$ m^3/kg

2.132

Use the computer software to find the properties for ammonia at the 2 states listed in Problem 2.32

Start the software, click the tab for cryogenic substances, and click the tab for the substance ammonia. Then click the small calculator icon and select the proper CASE for the given properties.

	CASE	RESULT
a)	2 (T, v)	Sup. vapor, x = undefined, $P = 1200$ kPa
b)	4 (T, x)	Two-phase, $P = 2033$ kPa, $v = 0.03257$ m^3/kg

2.133

Use the computer software to find the properties for ammonia at the 3 states listed in Problem 2.127

Start the software, click the tab for cryogenic substances, select ammonia and click the small calculator icon. Select the proper CASE for the given properties.

	CASE	RESULT
a)	8 (P, x)	$T = 6.795°C,\ v = 0.1719\ m^3/kg$
b)	1 (T, P)	Sup. vapor, x = undefined, $v = 1.773\ m^3/kg$
c)	2 (T, v)	Sup. vapor, x = undefined, $P = 330.4\ kPa$

2.134

Find the value of the saturated temperature for nitrogen by linear interpolation in table B.6.1 for a pressure of 900 kPa. Compare this to the value given by the computer software.

The 900 kPa in Table B.6.1 is located between 100 and 105 K.

$$T = 100 + (105 - 100)\,\frac{900 - 779.2}{1084.6 - 779.2}$$

$$= 100 + 5 \times 0.3955 = 101.98 \text{ K}$$

The actual curve has a positive second derivative (it curves up) so T is slightly underestimated by use of the chord between the 100 K and the 105 K points, as the chord is above the curve.

From the computer software:

CASE: 8 (P,x) $T = -171°C = 102.15$ K

So we notice that the curvature has only a minor effect.
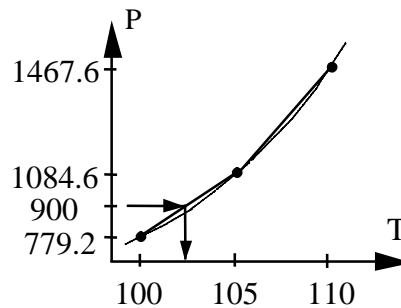
2.135

Use the computer software to sketch the variation of pressure with temperature in Problem 2.44. Extend the curve a little into the single-phase region.

P was found for a number of temperatures. A small table of (P, T) values were entered into a spreadsheet and a graph made as shown below. The superheated vapor region is reached at about 140°C and the graph shows a small kink at that point.
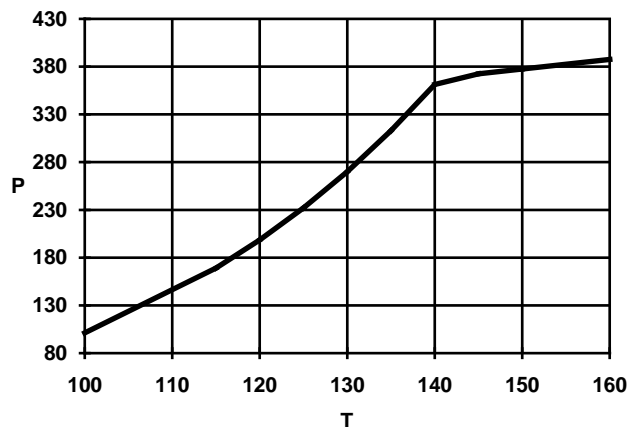
Borgnakke Sonntag

Fundamentals of Thermodynamics

SOLUTION MANUAL
CHAPTER 2
English Units

8e

CHAPTER 2

Concept Problems

2.136E

Cabbage needs to be cooked (boiled) at 250 F. What pressure should the pressure cooker be set for?

Solution:

If I need liquid water at 250 F, I must have a pressure that is at least the saturation pressure for this temperature.

Table F.7.1: 250 F P_{sat} = **29.823 psia.**

The pot must have a lid that can be fastened to hold the higher pressure, which is a pressure cooker.

2.137E

If I have 1 ft^3 of ammonia at 15 psia, 60 F how much mass is that?

Ammonia Tables F.8:

F.8.1 P_{sat} = 107.64 psia at 60 F so superheated vapor.

F.8.2   v = 21.5641 ft^3/lbm   under subheading 15 psia

$$m = \frac{V}{v} = \frac{1 \text{ ft}^3}{21.5641 \text{ ft}^3/\text{lbm}} = \textbf{0.0464 lbm}$$
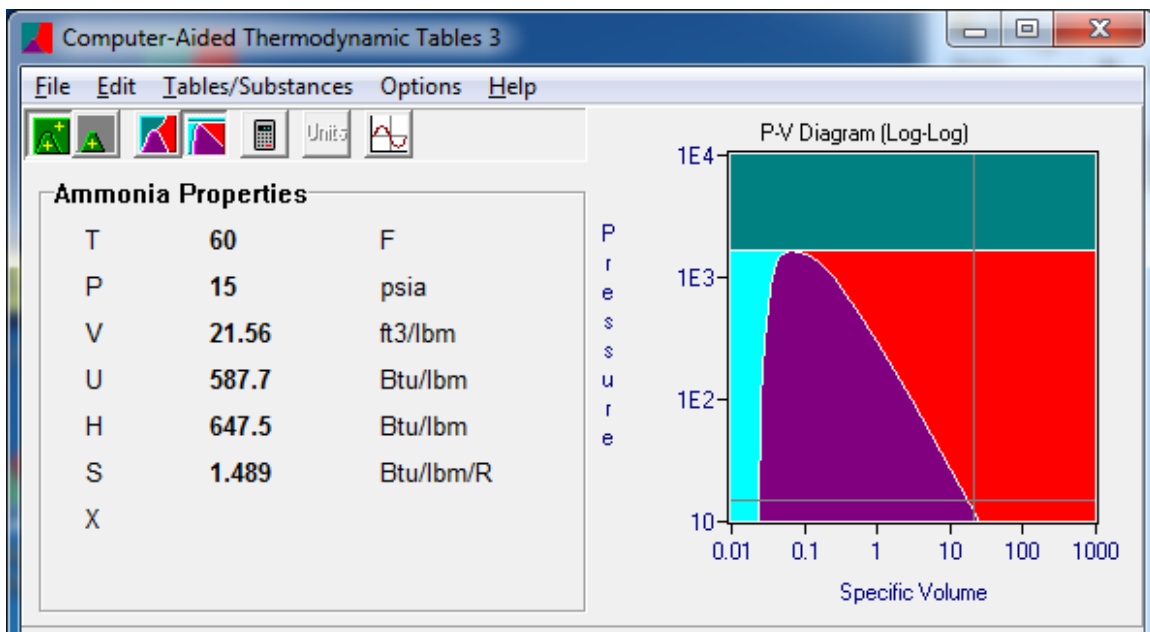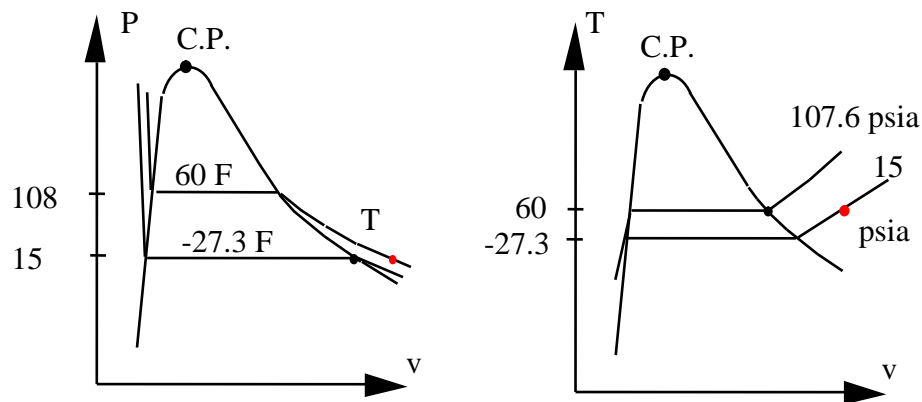
The P-v (log-log) diagram from CATT3, P in psi and v in ft^3/lbm. Cross-hair indicates the state.

2.138E

For water at 1 atm with a quality of 10% find the volume fraction of vapor.

This is a two-phase state at a given pressure:

Table F.7.2: $v_f = 0.01\ 672\ \text{ft}^3/\text{lbm}, \quad v_g = 26.8032\ \text{ft}^3/\text{lbm}$

From the definition of quality we get the masses from total mass, m, as

$$m_f = (1 - x)\ m, \qquad m_g = x\ m$$

The volumes are

$$V_f = m_f\ v_f = (1 - x)\ m\ v_f, \qquad V_g = m_g\ v_g = x\ m\ v_g$$

So the volume fraction of vapor is

$$\text{Fraction} = \frac{V_g}{V} = \frac{V_g}{V_g + V_f} = \frac{x\ m\ v_g}{x\ m\ v_g + (1 - x)m\ v_f}$$

$$= \frac{0.1 \times 26.8032}{0.1 \times 26.8032 + 0.9 \times 0.016\ 72} = \frac{2.68032}{2.69537} = \mathbf{0.9944}$$

Notice that the liquid volume is only about 0.5% of the total. We could also have found the overall $v = v_f + xv_{fg}$ and then $V = m\ v$.

2.139E

Locate the state of R-410A at 30 psia, -20 F. Indicate in both the P-v and the T-v diagrams the location of the nearest states listed in the printed table F.9

From F.9:   F.9.1 at -20 F, P_{sat} = 40.923 psi so we have superheated vapor.
F.9.2 at 30 psi we find the state for -20 F.
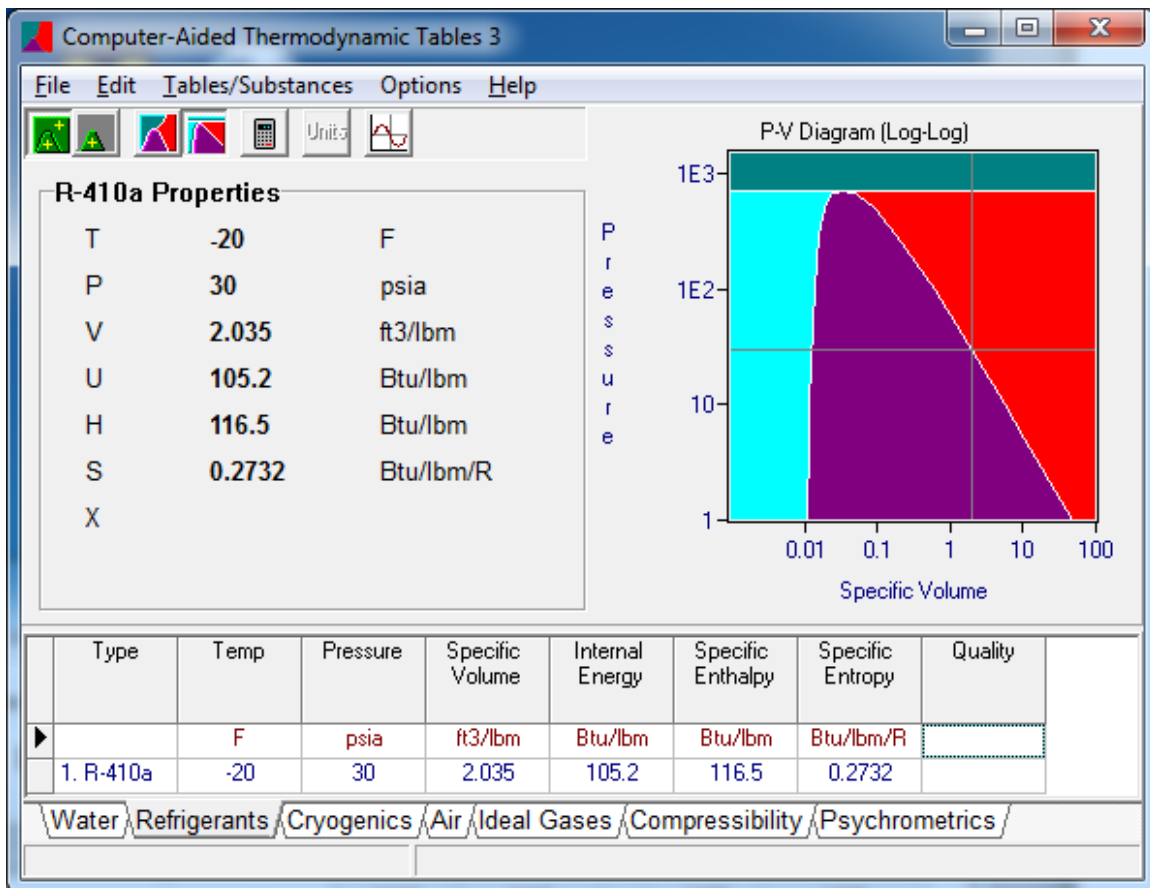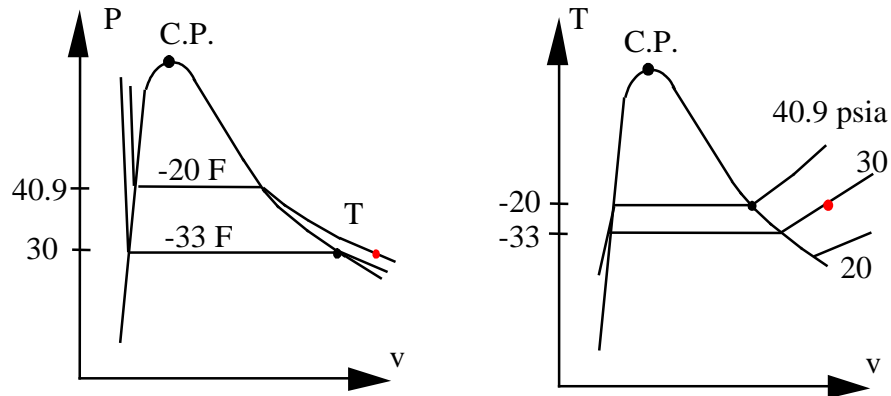
2.140E

Calculate the ideal gas constant for argon and hydrogen based on Table F.1 and verify the value with Table F.4

The gas constant for a substance can be found from the universal gas constant from table A.1 and the molecular weight from Table F.1

Argon: $R = \dfrac{\bar{R}}{M} = \dfrac{1.98589}{39.948} = 0.04971 \, \dfrac{\textbf{Btu}}{\textbf{lbm R}} = 38.683 \, \dfrac{\textbf{lbf-ft}}{\textbf{lbm R}}$

Hydrogen: $R = \dfrac{\bar{R}}{M} = \dfrac{1.98589}{2.016} = 0.98506 \, \dfrac{\textbf{Btu}}{\textbf{lbm R}} = 766.5 \, \dfrac{\textbf{lbf-ft}}{\textbf{lbm R}}$

Recall from Table A.1:   1 Btu = 778.1693 lbf-ft

Phase Diagrams

2.141E

Water at 80 F can exist in different phases dependent on the pressure. Give the approximate pressure range in lbf/in^2 for water being in each one of the three phases, vapor, liquid or solid.
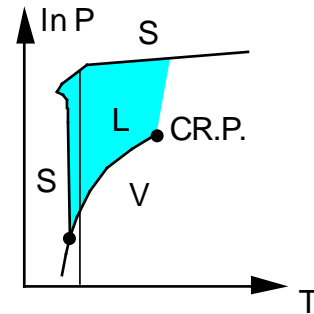
Solution:

The phases can be seen in Fig. 2.4, a sketch of which is shown to the right.

T = 80 F = 540 R = 300 K

From Fig. 2.4:

$P_{VL} \approx 4 \times 10^{-3}$ MPa = 4 kPa = 0.58 psia,

$P_{LS} = 10^3$ MPa = 145 038 psia

$$0 < P < \quad 0.58 \text{ psia} \quad \textbf{VAPOR}$$
$$\textbf{0.58 psia} \quad < P < 145\ 038 \text{ psia} \quad \textbf{LIQUID}$$
$$P > 145\ 038 \text{ psia} \quad \textbf{SOLID(ICE)}$$

2.142E

A substance is at 300 lbf/in.^{2}, 65 F in a rigid tank. Using only the critical properties can the phase of the mass be determined if the substance is oxygen, water or propane?

Solution: Find state relative to the critical point properties, Table F.1

a)   Oxygen   731 lbf/in.^{2} 278.3 R

b)   Water   3208 lbf/in.^{2} 1165.1 R

c)   Propane   616 lbf/in.^{2} 665.6 R

$P < P_c$ for all and $T = 65 \text{ F} = 65 + 459.67 = 525 \text{ R}$

a) O_2 $T \gg T_c$ Yes gas and $P < P_c$

b) H_2O $T \ll T_c$ $P \ll P_c$ so you cannot say

c) C_3H_8 $T \ < T_c$ $P < P_c$ you cannot say
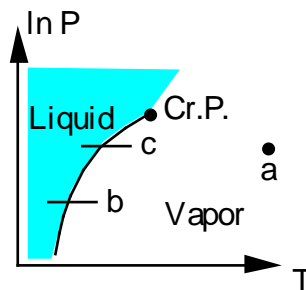
General Tables

2.143E

Determine the missing property (of P, T, v, and x if apllicable) for water at

        a.   680 lbf/in.^{2}, 0.03 ft^3/lbm

        b.   150 lbf/in.^{2}, 320 F

        c.   400 F, 3 ft^3/lbm
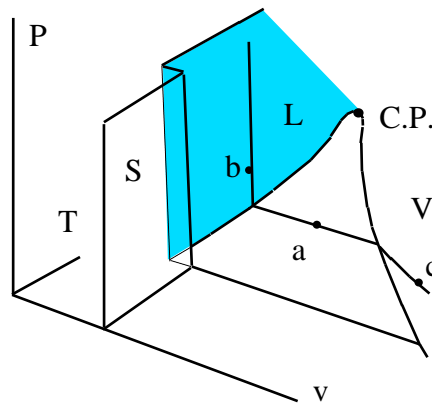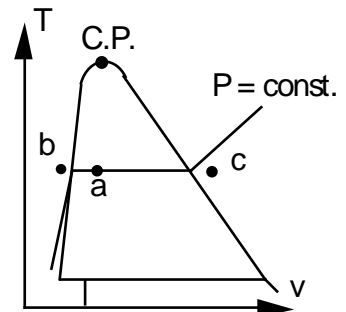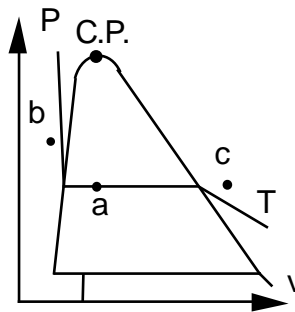
Solution: All cases can be seen from Table F.7.1

  a. 680 lbf/in.^{2}, 0.03 ft^3/lbm

        v_g = **0.2183,** v_f = **0.02472** ft^3/lbm, so **liquid + vapor mixture**

  b. 150 lbf/in.^{2}, 320 F: **compressed liquid** $P > P_{sat}(T)$ = **89.6 lbf/in^2**

  c. 400 F, 3 ft^3/lbm: **sup. vapor** $v > v_g(T)$ = **2.339** ft^3/lbm

States shown are placed relative to the two-phase region, not to each other.

2.144E

Determine the phase of the substance at the given state using Appendix F Tables.

Solution:

a. water 200 F, 70 psia:

F.7.1 at 200 F $P > P_{sat}(T) =$ **11.53 psia**   => **compressed liquid**

b. Ammonia 10 F, 20 lbf/in.^{2}:

F.8.1 at 10 F $P < P_{sat}(T) =$ **38.508 lbf/in^2** => **sup. vapor**

F.8.2:   Superheated by (20 – (-16.63)) F = 36.6 F, v = 14.7635 ft^3/lbm

c. R-410A 30 F, 50 ft^3/lbm

F.9.1 at 30 F: $P < P_{sat}(T) =$ **111.8 lbf/in^2** => **sup. vapor,**

F.9.2:   Interpolate to find v

The S-L fusion line goes slightly to the left for water. It tilts slightly to the right for most other substances.
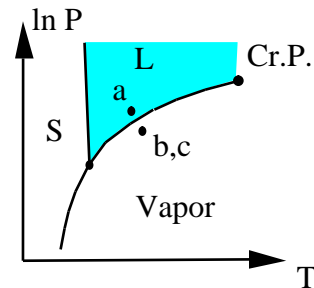
States shown are placed relative to the two-phase region, not to each other.
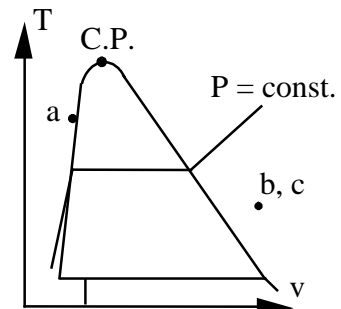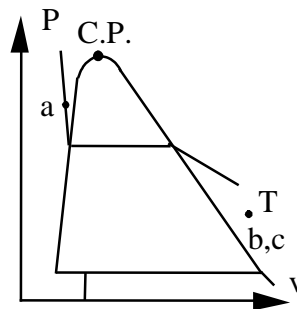
2.145E

Give the phase and the missing property of P, T, v and x for R-134a at
a.   T = -10 F, P = 18 psia
b.   P = 40 psia, v = 1.3 ft^3/lbm

Solution:

a. Look in Table F.10.1 at –10 F: P > P$_{sat}$ = 16.76 psia

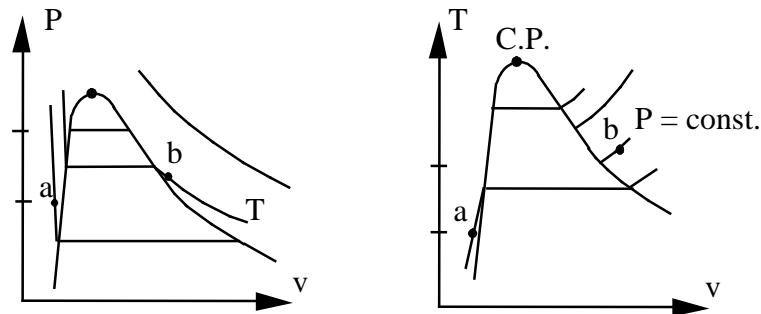   This state is **compressed liquid** so x is undefined and v = v$_f$ = 0.01173 ft^3/lbm

b. Look in Table F.10.1 close to 50 psia there we see

        v > v$_g$ = 0.95 ft^3/lbm   so   **superheated vapor**

   Look then in Table F.10.2 under 40 psia and interpolate between the 60 F and 80 F.

      (40 psia, 1.3 ft^3/lbm) :   T = 66.6 F

For a better accuracy use the computer software CATT3 which gives T = 67.4 F.

2.146E

Give the phase and the missing property of P, T, v and x for ammonia at
   a. $T = 120$ F, $v = 1.876$ ft^3/lbm
   b. $T = 120$ F, $x = 0.5$

Solution:

a. Look in Table F.8.1 at 120 F: $v > v_g = 1.0456$ ft^3/lbm so sup vap

   $x =$ undefined,   F.8.2 $P = 175$ psia

b. Look in Table F.8.1 at 120 F:

   $v = v_f + x\ v_{fg} = 0.02836 + 0.5 \times 1.0172 = 0.53696$ ft^3/lbm
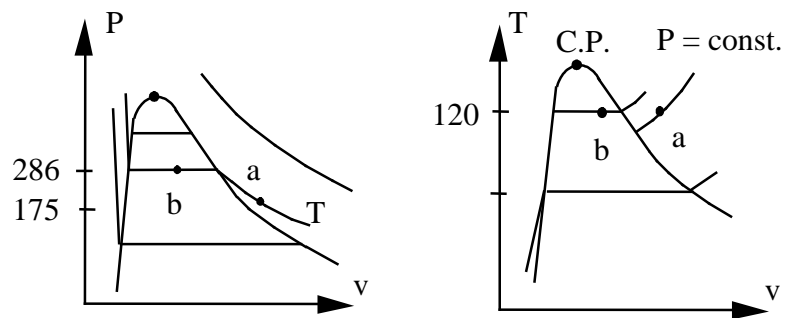
2.147E

Give the phase and the specific volume.

Solution:

a. R-410A $T = -25$ F, $P = 30$ lbf/in.^{2} Table F.9.2 $T > T_{sat} = -33.24$ F

$\Rightarrow$ **sup.vap.** $v \cong 1.9534 + \dfrac{-25+33.24}{-20+33.24}(2.0347 - 1.9534) =$ **2.004 ft^3/lbm**

b. R-410A $T = -25$ F, $P = 40$ lbf/in.^{2} Table F.9.2 $T < T_{sat} = -21.0$ F

$P > P_{sat} \Rightarrow$ **compresssed Liquid**   F.9.1: $v \cong v_f =$ **0.01246 ft^3/lbm**

c. H$_2$O $T = 280$ F, $P = 35$ lbf/in.^{2} Table F.7.1 $P < P_{sat} = 49.2$ psia

$\Rightarrow$ **superheated vapor**

$v \cong 21.734 + (10.711 - 21.734) \times (15/20) =$ **1.0669 ft^3/lbm**

d. NH$_3$ $T = 60$ F, $P = 15$ lbf/in.^{2} Table F.8.1 $P_{sat} = 107.6$ psia

$P < P_{sat} \Rightarrow$ **superheated vapor** $v \cong$ **21.564 ft^3/lbm**

States shown are
placed relative to the
two-phase region, not
to each other.
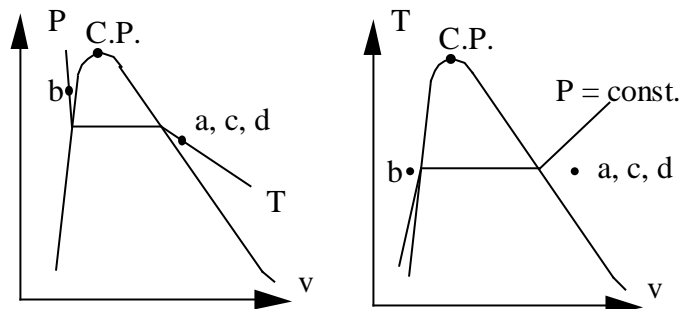
2.148E

Determine the specific volume for R-410A at these states:
   a. 20 F, 70 psia
   b. 70 F, 150 psia
   c. 70 F, quality 25%

a. F.9.2 $P < P_{sat} = 93.13$ psia so sup vapor.

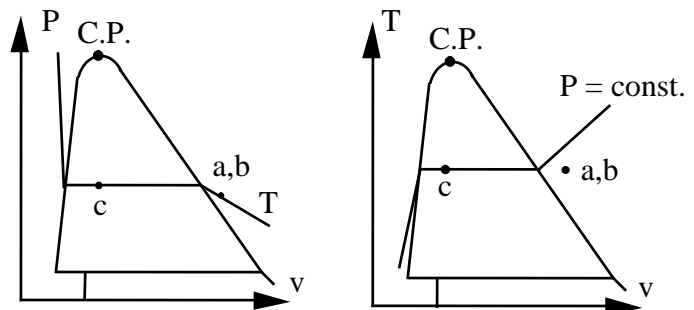$$v = 1.0783 + \frac{70 - 60}{75 - 60}(0.8393 - 1.0783) = \mathbf{0.9190 \ ft^3/lbm}$$

b. F.9.1 $P < P_{sat} = 215.95$ psia   so superheated vapor

F.9.2: $v = 0.4236 + \frac{70 - 60}{80 - 60}(0.4545 - 0.4236) = \mathbf{0.43905 \ ft^3/lbm}$

c. F.9.1 $v_f = 0.01486 \ ft^3/lbm, \ v_{fg} = 0.2576 \ ft^3/lbm$

$v = v_f + x \ v_{fg} = 0.01486 + 0.25 \times 0.2576 = \mathbf{0.07926 \ ft^3/lbm}$

States shown are
placed relative to the
two-phase region, not
to each other.

2.149E

Give the missing property of P, T, v and x for

     a. R-410A at 80 F, $v = 0.2$ ft^3/lbm

     b. R-410A at 60 psia, $v = 1.1$ ft^3/lbm

     c. Ammonia at 60 F, $v = 3.2$ ft^3/lbm

a) Table F.9.1 at 80 F: $v < v_g = 0.2308$ ft^3/lbm so we have 2 phase L+V

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.2 - 0.01525}{0.2156} = \textbf{0.8569};\ \ P = P_{sat} = \textbf{250.665 psia}$$

b) Table F.9.2 at 60 psia: $v > v_g = 1.0038$ ft^3/lbm so we have superheated vapor
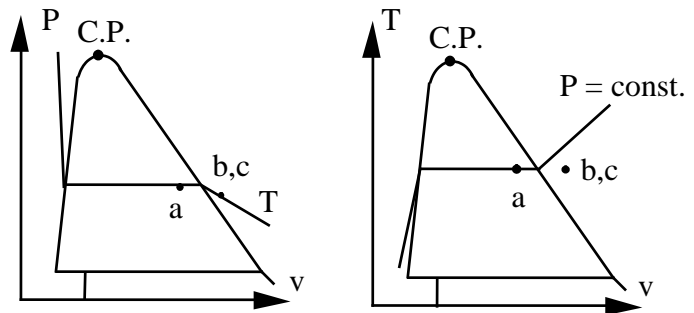
   so x is undefined.

     F.9.2 between 20 and 40 F:

$$T = 20 + 20 \times \frac{1.1 - 1.0783}{1.1405 - 1.0783} = \textbf{26.98 F}$$

c) Table F.8.1 at 60 F: $v > v_g = 2.7481$ ft^3/lbm so we have superheated vapor.

     F.8.2 between 90 and 100 psia:

$$P = 90 + 10 \times \frac{3.2 - 3.3503}{2.9831 - 3.3503} = \textbf{94.09 psia}$$

States shown are
placed relative to the
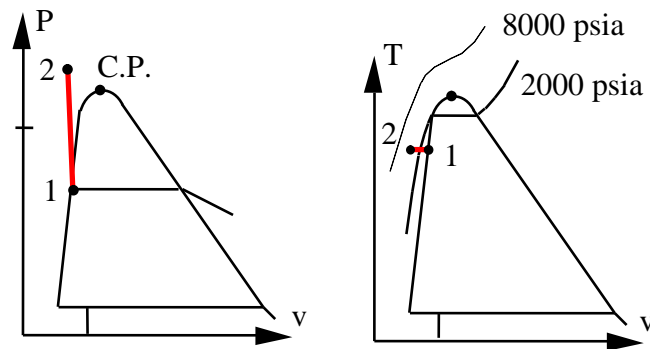two-phase region, not
to each other.

2.150E

Saturated liquid water at 150 F is put under pressure to decrease the volume by 1% while keeping the temperature constant. To what pressure should it be compressed?

F.7.1: $v = v_f = 0.01634$ ft^3/lbm

New v: $v = 0.99\ v_f = 0.0161766$ ft^3/lbm

look in F.7.3:   close to 2000 psia

interpolate between 2000 and 8000 psia   P = **2610 psia**

2.151E

A sealed rigid vessel has volume of 35 ft^3 and contains 2 lbm of water at 200 F. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 400 F?

Solution:

Process: v = V/m = constant

State 1: v_1 = 35/2 = 17.5 ft^3/lbm
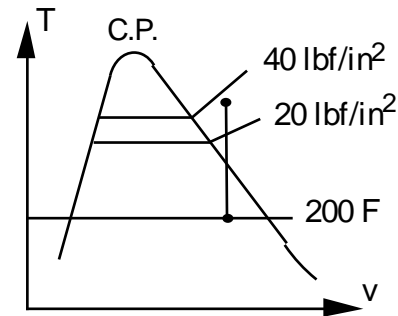
from Table F.7.1

it is 2-phase

State 2: 400°F, 17.5 ft^3/lbm

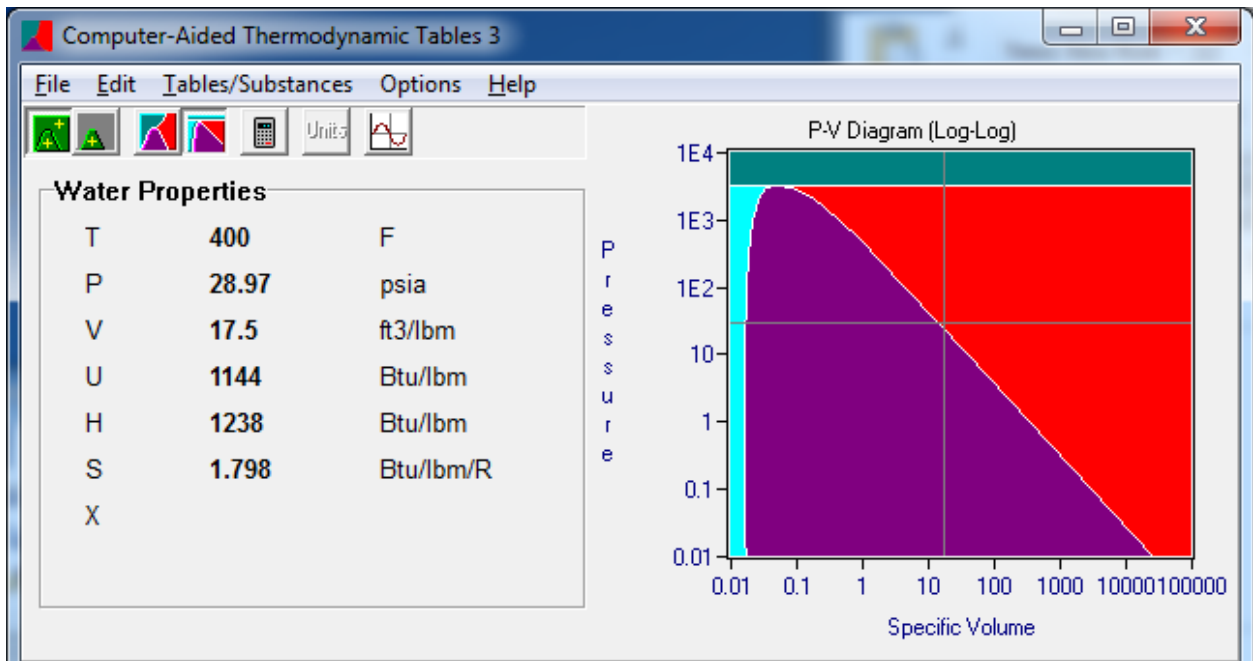Table F.7.2 between 20

and 40 lbf/in^2 so interpolate

$$P \cong 20 + (40 - 20) \frac{17.5 - 25.427}{12.623 - 25.427} = \textbf{32.4 lbf/in}^2$$

(The result is 28.97 psia if found by the software, i.e. linear interpolation is not so accurate)

2.152E

You want a pot of water to boil at 220 F. How heavy a lid should you put on the 6 inch diameter pot when P_{atm} = 14.7 psia?

Solution:

Table F.7.1 at 220 F : P_{sat} = 17.189 psia

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}\ 6^2 = 28.274\ in^2$$

$$F_{net} = (P_{sat} - P_{atm})\ A = (17.189 - 14.7)\ (lbf/\ in^2) \times 28.274\ in^2$$
$$= 70.374\ lbf$$

$$F_{net} = m_{lid}\ g$$

$$m_{lid} = F_{net}/g = \frac{70.374\ lbf}{32.174\ ft/s^2} = \frac{70.374 \times 32.174\ lbm\ ft/s^2}{32.174\ ft/s^2} = \textbf{70.374 lbm}$$

Some lids are clamped on, the problem deals with one that stays on due to its weight.
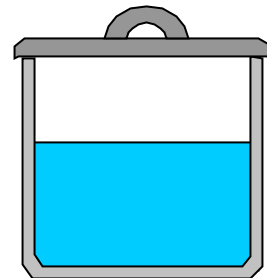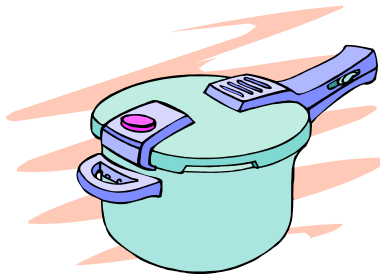
2.153E

Saturated water vapor at 240 F has its pressure decreased to increase the volume by 10%, keeping the temperature constant. To what pressure should it be expanded?

Solution:

Initial state: $\quad$ v = 16.3257 ft³/lbm $\quad$ from table F.7.1

Final state: $\quad$ v = 1.1 × v_g = 1.1 × 16.3257 = 17.9583 ft³/lbm

Interpolate between sat. at 240 F, P = 24.968 lbf/in² and sup. vapor in Table F.7.2 at 240 F, 20 lbf/in²

$$P = 24.968 + (20 - 24.968)\,\frac{17.9583 - 16.3257}{20.475 - 16.3257}$$

$$\cong \mathbf{23.0\ lbf/in^2}$$
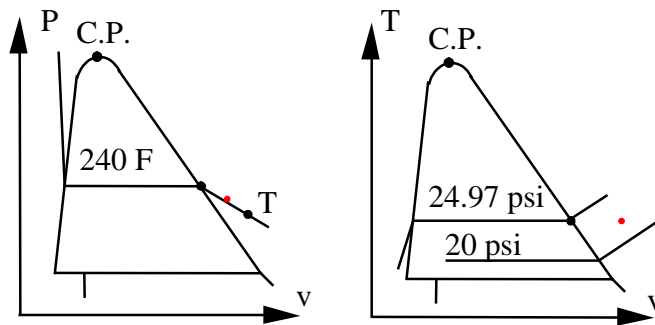
2.154E

A glass jar is filled with saturated water at 300 F and quality 25%, and a tight lid is put on. Now it is cooled to 10 F. What is the mass fraction of solid at this temperature?

Solution:

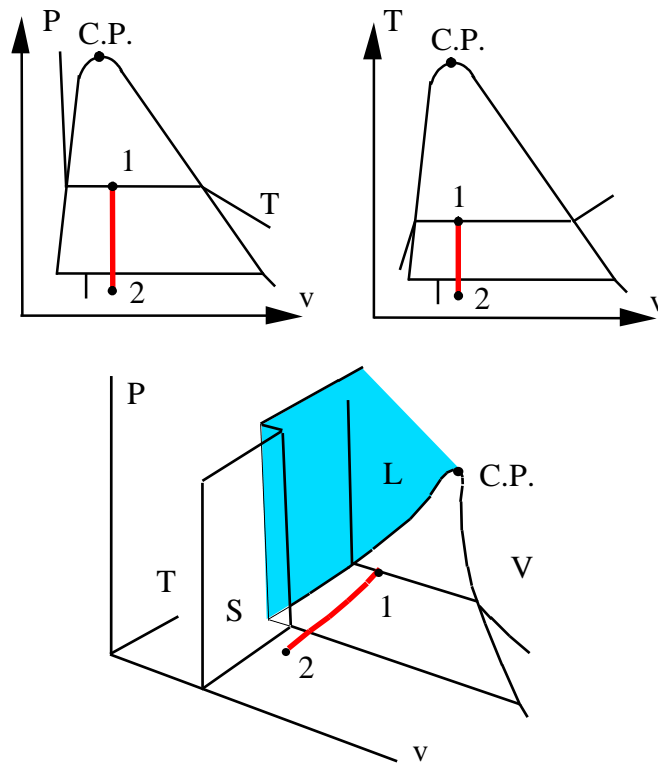Constant volume and mass $\Rightarrow v_1 = v_2 = V/m$

From Table F.7.1: $\qquad v_1 = 0.01745 + 0.25 \times 6.4537 = 1.630875 \ \text{ft}^3/\text{lbm}$

From Table F.7.4: $\qquad v_2 = 0.01744 + x_2 \times 9043 = v_1 = 1.630875 \ \text{ft}^3/\text{lbm}$

$\qquad\qquad\qquad\qquad \Rightarrow x_2 = 0.000178 \ \text{ mass fraction vapor}$

$x_{solid} = 1 - x_2 = 0.9998 \qquad \text{or} \qquad \textbf{99.98 \%}$

2.155E

A boiler feed pump delivers 100 ft^3/min of water at 400 F, 3000 lbf/in.^{2}. What is the mass flowrate (lbm/s)? What would be the percent error if the properties of saturated liquid at 400 F were used in the calculation? What if the properties of saturated liquid at 3000 lbf/in.^{2} were used?

Solution:

Table F.7.3: $v = 0.0183$ ft^3/lbm (interpolate 2000-8000 psia)

$$\dot{m} = \frac{\dot{V}}{v} = \frac{100}{60 \times 0.018334} = 91.07 \text{ lbm/s}$$

$v_{f\,(400\,F)} = 0.01864$ ft^3/lbm $\Rightarrow$ $\dot{m} = 89.41$ lbm/s **error 1.8%**

$v_{f\,(3000\,lbf/in^2)} = 0.03475$ ft^3/lbm $\Rightarrow$ $\dot{m} = 47.96$ lbm/s **error 47%**
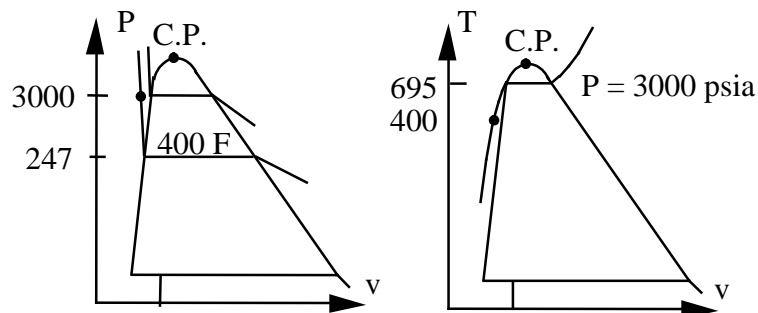
The constant T line is nearly vertical for the liquid phase in the P-v diagram. The state is at so high P, T that the saturated liquid line is not extremely steep.

2.156E

A pressure cooker has the lid screwed on tight. A small opening with A = 0.0075 in² is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at 250 F with an outside atmosphere at 15 psia?

Solution:

Table F.7.1 at 250 F: $P_{sat} = 29.823$ psia

$F_{net} = (P_{sat} - P_{atm})\ A = (29.823 - 15)$ psia $\times\ 0.0075$ in²
        = 0.111 lbf

$F_{net} = m_{petcock}\ g$

$m_{petcock} = F_{net}/g = \dfrac{0.111\ lbf}{32.174\ ft/s^2} = \dfrac{0.111 \times 32.174\ lbm\ ft/s^2}{32.174\ ft/s^2} =$ **0.111 lbm**

Some petcocks are held down by a spring, the problem deals with one that stays on due to its weight.

2.157E

Two tanks are connected together as shown in Fig. P2.52, both containing water. Tank A is at 30 lbf/in.^{2}, $v = 8$ ft^3/lbm, $V = 40$ ft^3 and tank B contains 8 lbm at 80 lbf/in. ^{2}, 750 F. The valve is now opened and the two come to a uniform state. Find the final specific volume.

Solution:

Control volume both tanks. Constant total volume and mass process.
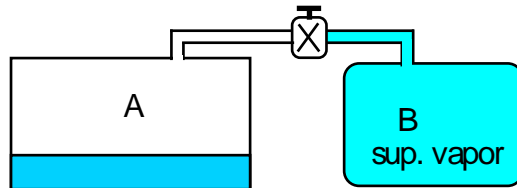
State A1: (P, v) two-phase, $m_A = V_A/v_A = 40$ ft^3 /8 ft^3/lbm $= 5$ lbm

State B1: (P, T) Table F.7.2: $v_B = (8.561 + 9.322)/2 = 8.9415$ ft^3/lbm

$\Rightarrow V_B = m_B v_B = 8$ lbm $\times 8.9415$ ft^3/lbm $= 71.532$ ft^3

Final state: $m_{tot} = m_A + m_B = 5 + 8 = 13$ lbm

$V_{tot} = V_A + V_B = 111.532$ ft^3

$v_2 = V_{tot}/m_{tot} = 111.532$ ft^3/13 lbm $=$ **8.579 ft^3/lbm**

2.158E

Ammonia at 70 F with a quality of 50% and total mass 4.5 lbm is in a rigid tank with an outlet valve at the bottom. How much liquid (mass) can you take out through the valve assuming the temperature stays constant?

Solution:

The bottom has liquid until the state inside becomes saturated vapor.
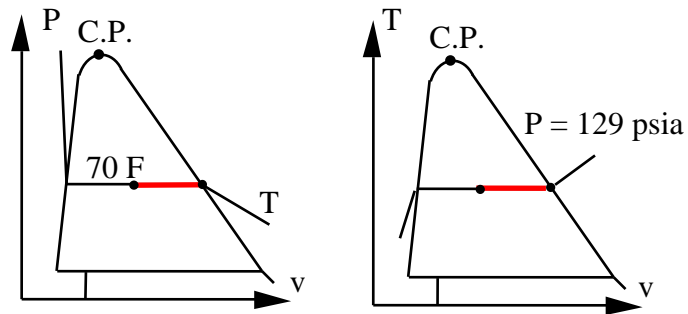
$$V = m_1 v_1 = 4.5 \times 0.5 \, (0.02631 + 2.3098) = 5.25625 \text{ ft}^3$$

$$m_2 = V/v_2 = 5.25625 \text{ ft}^3/ \, 2.3098 \text{ ft}^3/\text{lbm} = 2.2756 \text{ lbm}$$

$$m = m_1 - m_2 = 4.5 - 2.2756 = \textbf{2.224 lbm}$$

Ideal Gas

2.159E

Give the phase and the specific volume for each of the following.
Solution:

a. CO_2 $T = 510$ F $P = 75$ lbf/in.^{2} Table F.4

superheated vapor ideal gas

$$v = RT/P = \frac{35.1 \text{ ft-lbf/lbm-R} \times (510 + 459.7) \text{ R}}{75 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$$

$$= \textbf{3.152 ft}^3\textbf{/lbm}$$

b.   Air $T = 68$ F $P = 2$ atm   Table F.4

superheated vapor ideal gas

$$v = RT/P = \frac{53.34 \text{ ft-lbf/lbm-R} \times (68 + 459.7) \text{ R}}{2 \times 14.6 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$$

$$= \textbf{6.6504 ft}^3\textbf{/lbm}$$

c.   Ar $T = 300$ F, $P = 30$ lbf/in.^{2} Table F.4

Ideal gas: $v = RT/P = \dfrac{38.68 \text{ ft-lbf/lbm-R} \times (300 + 459.7) \text{ R}}{30 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$

$$= \textbf{6.802 ft}^3\textbf{/lbm}$$

2.160E

A cylindrical gas tank 3 ft long, inside diameter of 8 in., is evacuated and then filled with carbon dioxide gas at 77 F. To what pressure should it be charged if there should be 2.6 lbm of carbon dioxide?

Solution:

Assume CO_2 is an ideal gas table F.4: $P = mRT/V$

$$V_{cyl} = A \times L = \frac{\pi}{4}(8 \text{ in})^2 \times 3 \times 12 \text{ in} = 1809.6 \text{ in}^3$$

$$P = \frac{2.6 \text{ lbm} \times 35.1 \text{ ft-lbm/lbm-R} \times (77 + 459.67) \text{ R} \times 12 \text{ in/ft}}{1809.6 \text{ in}^3}$$

$$= \mathbf{324.8 \text{ lbf/in}^2}$$

2.161E

A spherical helium balloon of 30 ft in diameter is at ambient T and P, 60 F and 14.69 psia. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?

We need to find the masses and the balloon volume

$$V = \frac{\pi}{6} D^3 = \frac{\pi}{6} 30^3 = 14\ 137\ \text{ft}^3$$

$$m_{He} = \rho V = \frac{V}{v} = \frac{PV}{RT}$$

$$= \frac{14.69\ \text{psi} \times 14\ 137\ \text{ft}^3 \times 144\ (\text{in/ft})^2}{386.0\ \text{ft-lbf/lbmR} \times 520\ \text{R}}$$

$$= 148.99\ \text{lbm}$$

$$m_{air} = \frac{PV}{RT} = \frac{14.69\ \text{psi} \times 14\ 137\ \text{ft}^3 \times 144\ (\text{in/ft})^2}{53.34\ \text{ft-lbf/lbmR} \times 520\ \text{R}}$$

$$= 1078\ \text{lbm}$$

$$m_{lift} = m_{air} - m_{He} = 1078 - 149 = \textbf{929 lbm}$$

2.162E

Helium in a steel tank is at 36 psia, 540 R with a volume of 4 ft^3. It is used to fill a balloon. When the pressure drops to 18 psia, the flow of helium stops by itself. If all the helium still is at 540 R, how big a balloon is produced?

Solution:

State 1:   m = V/v   assume ideal gas so

$$m = \frac{P_1 V_1}{RT_1} = \frac{36 \text{ psi} \times 4 \text{ ft}^3 \times 144 \text{ (in/ft)}^2}{386 \text{ ft-lbf/lbmR} \times 540 \text{ R}}$$

$$= 0.0995 \text{ lbm}$$

State 2:   Same mass so then (T$_2$ = T$_1$)

$$V_2 = \frac{mRT_2}{P_2} = \frac{P_1 V_1}{RT_1} \frac{RT_2}{P_2} = V_1 \frac{P_1}{P_2}$$

$$= 4 \frac{36}{18} = 8 \text{ ft}^3$$

The balloon volume is

$$V_{balloon} = V_2 - V_1 = 8 - 4 = \mathbf{4 \ ft^3}$$
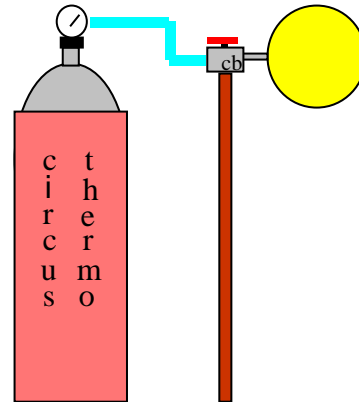
Review Problems

2.163E

A 35 ft^3 rigid tank has propane at 15 psia, 540 R and connected by a valve to another tank of 20 ft^3 with propane at 40 psia, 720 R. The valve is opened and the two tanks come to a uniform state at 600 R. What is the final pressure?

Solution:

Propane is an ideal gas (P $<<$ P$_c$) with R = 35.04 ft-lbf/lbm R from Tbl. F.4

$$m_A = \frac{P_A V_A}{RT_A} = \frac{15 \times 35 \times 144}{35.04 \times 540} = 3.995 \text{ lbm}$$

$$m = \frac{P_B V_B}{RT_B} = \frac{40 \times 20 \times 144}{35.04 \times 720} = 4.566 \text{ lbm}$$

$$V_2 = V_A + V_B = 55 \text{ ft}^3$$

$$m_2 = m_A + m_B = 8.561 \text{ lbm}$$
$$P_2 = \frac{m_2 R T_2}{V_2} = \frac{8.561 \times 35.04 \times 600}{55 \times 144} = \textbf{22.726 psia}$$

2.164E

What is the percent error in specific volume if the ideal gas model is used to represent the behavior of superheated ammonia at 100 F, 80 lbf/in.^{2}? What if the generalized compressibility chart, Fig. D.1, is used instead?

Solution:

Ammonia Table F.8.2: $v = 4.186 \text{ ft}^3/\text{lbm}$

Ideal gas $v = \dfrac{RT}{P} = \dfrac{90.72 \times 559.7}{80 \times 144} = 4.4076 \text{ ft}^3/\text{lbm}$ **5.3% error**

Generalized compressibility chart and Table D.4

$$T_r = 559.7/729.9 = 0.767, \ \ P_r = 80/1646 = 0.0486$$

$$\Rightarrow \quad Z \cong 0.96$$

$$v = \dfrac{ZRT}{P} = 0.96 \times 4.4076 \text{ ft}^3/\text{lbm} = 4.231 \text{ ft}^3/\text{lbm} \quad \textbf{1.0\% error}$$

2.165E

Air in an internal combustion engine has 440 F, 150 psia with a volume of 2 ft^3. Now combustion heats it to 3000 R in a constant volume process. What is the mass of air and how high does the pressure become?

The mass comes from knowledge of state 1 and ideal gas law

$$m = \frac{P_1 V_1}{RT_1} = \frac{150 \text{ psia} \times 2 \text{ ft}^3 \times 144 \text{ (in/ft)}^2}{53.34 \text{ ft-lbf/lbm-R} \times (440 + 459.67) \text{ R}} = \textbf{0.90 lbm}$$

The final pressure is found from the ideal gas law written for state 1 and state 2 and then eliminate the mass, gas constant and volume ($V_2 = V_1$) between the equations

$$P_1 \, V_1 = m \, RT_1 \qquad \text{and} \qquad P_2 \, V_2 = m \, RT_2$$

$$P_2 = P_1 \times T_2/T_1 = 150 \text{ psia} \times \frac{3000}{440 + 459.67} = \textbf{500.2 psia}$$

2.166E

A 35 ft^3 rigid tank has air at 225 psia and ambient 600 R connected by a valve to a piston cylinder. The piston of area 1 ft^2 requires 40 psia below it to float, Fig. P2.166. The valve is opened and the piston moves slowly 7 ft up and the valve is closed. During the process air temperature remains at 600 R. What is the final pressure in the tank?

$$m_A = \frac{P_A V_A}{RT_A} = \frac{225 \text{ psia} \times 35 \text{ ft}^3 \times 144 \text{ (in/ft)}^2}{53.34 \text{ ft-lbf/lbm-R} \times 600 \text{ R}} = 35.433 \text{ lbm}$$

$$m_{B2} - m_{B1} = \frac{\Delta V_A}{v_B} = \frac{\Delta V_B P_B}{RT} = \frac{40 \text{ psia} \times (1 \times 7) \text{ ft}^3 \times 144 \text{ (in/ft)}^2}{53.34 \text{ ft-lbf/lbm-R} \times 600 \text{ R}}$$
$$= 1.26 \text{ lbm}$$

$$m_{A2} = m_A - (m_{B2} - m_{B1}) = 35.433 - 1.26 = 34.173 \text{ lbm}$$

$$P_{A2} = \frac{m_{A2}RT}{V_A} = \frac{34.173 \times 53.34 \times 600}{35 \times 144} = \textbf{217 psia}$$

2.167E

Give the phase and the missing properties of *P*, *T*, *v* and *x*. These may be a little more difficult if the appendix tables are used instead of the software.
Solution:

a. R-410A at $T = 50$ F, $v = 0.4$ ft^3/lbm: Table F.9.1: $v > v_g = 0.3818$ ft^3/lbm

   sup. vap. F.9.2 interpolate between sat. and sup. vap at 50 F.
   Find v at 150 psia, 50 F: $v = 0.4066$
   Now interpolate between the sat vap 157.473 psia and the 150 psia.

   $P \cong 150 + 7.473 \, (0.4 - 0.4066)/(0.3818 - 0.4066) = \mathbf{152\ lbf/in^2}$

b. H$_2$O $\quad v = 2$ ft^3/lbm, $x = 0.5$: $\qquad$ Table F.7.1

   since v_f is so small we find it approximately where $v_g = 4$ ft^3/lbm.

   $v_f + v_g = 4.3293$ at 330 F, $\quad v_f + v_g = 3.80997$ at 340 F.

   linear interpolation $\quad$ **T $\cong$ 336 F, P $\cong$ 113 lbf/in^2**

c. H$_2$O $\quad T = 150$ F, $v = 0.01632$ ft^3/lbm: $\qquad$ Table F.7.1, $v < v_f$

   compr. liquid $P \cong \mathbf{500\ lbf/in^2}$

d. NH$_3$ $\quad T = 80$ F, $P = 13$ lbf/in.^{2} $\qquad$ Table F.8.1 $\quad P < P_{sat}$

   sup. vap. interpolate between 10 and 15 psia: $\quad v = \mathbf{26.97\ ft^3/lbm}$
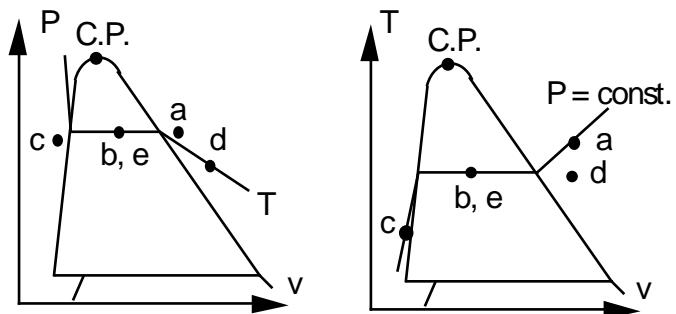   v is not linear in P (more like 1/P) so computer table is more accurate.

e. R-134a $\quad v = 0.08$ ft^3/lbm, x = 0.5: Table F.10.1

   since v_f is so small we find it approximately where $v_g = 0.16$ ft^3/lbm.

   $v_f + v_g = 0.1729$ at 150 F, $\quad v_f + v_g = 0.1505$ at 160 F.

   linear interpolation $\qquad$ **T $\cong$ 156 F, P $\cong$ 300 lbf/in^2**

States shown are
placed relative to the
two-phase region, not
to each other.

2.168E

A pressure cooker (closed tank) contains water at 200 F with the liquid volume being 1/10 of the vapor volume. It is heated until the pressure reaches 300 lbf/in.^{2}. Find the final temperature. Has the final state more or less vapor than the initial state?
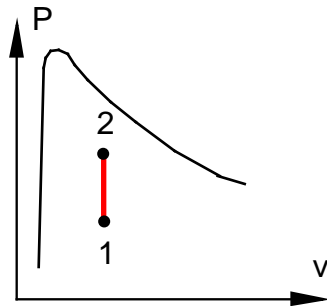
Solution:

Process: Constant volume and mass.

$$V_f = m_f\, v_f = V_g/10 = m_g v_g/10;$$

Table F.7.1: $v_f = 0.01663\ \text{ft}^3/\text{lbm},\quad v_g = 33.631\ \text{ft}^3/\text{lbm}$

$$x_1 = \frac{m_g}{m_g + m_f} = \frac{10\, m_f v_f / v_g}{m_f + 10\, m_f v_f / v_g} = \frac{10\, v_f}{10\, v_f + v_g} = \frac{0.1663}{0.1663 + 33.631} = 0.00492$$

$$v_2 = v_1 = 0.01663 + x_1 \times 33.615 = 0.1820\ \text{ft}^3/\text{lbm}$$

$$P_2, v_2 \implies \quad T_2 = T_{sat}(300\ \text{psia}) = \mathbf{417.43\ F}$$

At state 2: $v_2 = v_f + x_2\, v_{fg}$

$0.1820 = 0.01890 + x_2 \times 1.5286$

$\implies\ x_2 = \mathbf{0.107}$

More vapor at final state

2.169E

Refrigerant-410A in a piston/cylinder arrangement is initially at 60 F, x = 1. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 30 lbf/in.^{2}. Find the final temperature and specific volume.

Solution:

State 1: $P_1 = 184.98$ lbf/in^2 $v_1 = 0.3221$ ft^3/lbm

Process: $Pv = C = P_1v_1 = P_2v_2$

State 2: $P_2 = 30$ lbf/in^2 and on process line (equation).

$$v_2 = \frac{v_1P_1}{P_2} = 0.\,3221 \times 184.98 \,/\, 30 = \mathbf{1.9861 \; ft^3/lbm}$$

Table F.9.2 between saturated at -33.24 F and -20 F: $T_2 \cong$ **-27.9 F**

Notice T is **not** constant
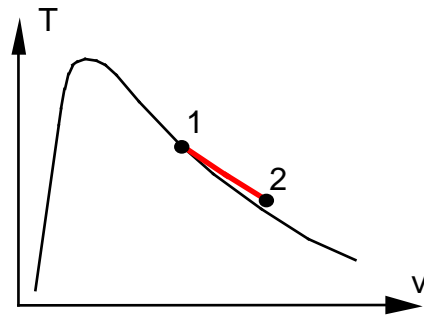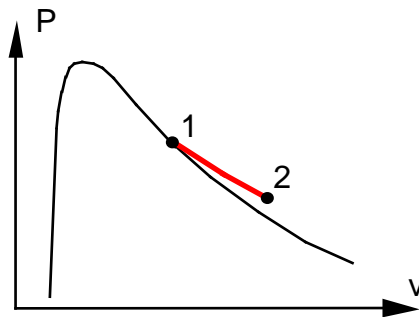
Compressiblity Factor

2.170E

A substance is at 70 F, 300 lbf/in.^{2} in a 10 ft^3 tank. Estimate the mass from the compressibility chart if the substance is a) air, b) butane or c) propane.

Solution:

Use Fig. D.1 for compressibility Z and table F.1 for critical properties

$$m = \frac{PV}{ZRT} = \frac{300 \times 144 \times 10}{530 \, ZR} = \frac{815.09}{ZR}$$

Air use nitrogen $P_c = 492$ lbf/in.^{2}; $T_c = 227.2$ R

$\qquad P_r = 0.61;\quad T_r = 2.33;\quad Z = 0.98$

$$m = \frac{PV}{ZRT} = \frac{815.09}{ZR} = \frac{815.09}{0.98 \times 55.15} = \textbf{15.08 lbm}$$

Butane $P_c = 551$ lbf/in.^{2}; $T_c = 765.4$ R

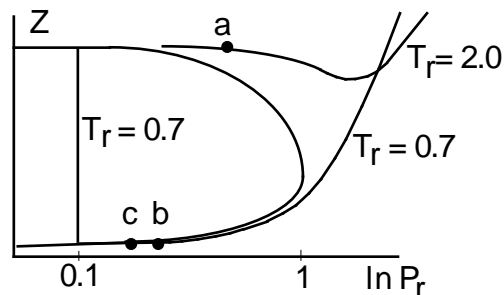$\qquad P_r = 0.544;\quad T_r = 0.692;\quad Z = 0.09$

$$m = \frac{PV}{ZRT} = \frac{815.09}{ZR} = \frac{815.09}{0.09 \times 26.58} = \textbf{340.7 lbm}$$

Propane $P_c = 616$ lbf/in.^{2}; $T_c = 665.6$ R

$\qquad P_r = 0.487;\quad T_r = 0.796;\quad Z = 0.08$

$$m = \frac{PV}{ZRT} = \frac{815.09}{ZR} = \frac{815.09}{0.08 \times 35.04} = \textbf{290.8 lbm}$$

2.171E

Determine the mass of an ethane gas stored in a 25 ft^3 tank at 250 F, 440 lbf/in.^{2} using the compressibility chart. Estimate the error (%) if the ideal gas model is used.

Solution

Table F.1: $T_r = (250 + 460) / 549.7 = 1.29$ and $P_r = 440/708 = 0.621$

Figure D.1 $\Rightarrow$ $Z = 0.9$

$$m = \frac{PV}{ZRT} = \frac{440 \text{ psia} \times 25 \text{ ft}^3 \times 144 \text{ (in/ft)}^2}{0.9 \times 51.38 \text{ ft-lbf/lbm-R} \times 710 \text{ R}} = \textbf{48.25 lbm}$$

Ideal gas $Z = 1$

$\Rightarrow$ $m = PV/RT = 43.21$ lbm   **10% error**

Equations of State

2.172E

Determine the pressure of R-410A at 100 F, $v = 0.2$ ft^3/lbm using ideal gas and the van der Waal Equation of State.

From F.1 for R-410A: $M = 72.585$, $T_c = 620.1$ R, $P_c = 711$ psia

For ideal gas we get:

$$R = \bar{R}/M = 1545.36 / 72.585 = 21.29 \text{ lbf-ft/lbm-R}$$

$$P = RT/v = \frac{21.29 \times (100 + 459.67)}{0.2 \times 144} \frac{\text{lbf-ft}}{\text{lbm-R}} \frac{R}{\text{ft}^3/\text{lbm} \times (\text{in./ft})^2}$$

$$= \textbf{413.73 psi}$$

For **van der Waal equation of state** from Table D.1 we have

$$b = \frac{1}{8}\frac{RT_c}{P_c} = 0.125 \times \frac{21.29 \times 620.1}{711 \times 144} = 0.016\ 118 \text{ ft}^3/\text{lbm},$$

$$a = 27\ b^2\ P_c = 27 \times (0.016\ 118)^2 \times 711 = 4.987\ 283 \text{ psi (ft}^3/\text{lbm})^2$$

The EOS is: $P = \dfrac{RT}{v-b} - \dfrac{a}{v^2} = \dfrac{21.29 \times 559.67/144}{0.2 - 0.016\ 118} - \dfrac{4.987\ 283}{0.2^2} = \textbf{325.3 psi}$

From Table F.9.2 we see it is around 300 psia.

2.173E

Determine the pressure of R-410A at 100 F, v = 0.2 ft^3/lbm using ideal gas and the Redlich-Kwong Equation of State.

From F.1 for R-410A: M = 72.585, T_c = 620.1 R, P_c = 711 psia

For ideal gas we get:

$$R = \bar{R}/M = 1545.36 \,/\, 72.585 = 21.29 \text{ lbf-ft/lbm-R}$$

$$P = RT/v = \frac{21.29 \times (100 + 459.67)}{0.2 \times 144} \frac{\text{lbf-ft}}{\text{lbm-R}} \frac{R}{\text{ft}^3/\text{lbm} \times (\text{in./ft})^2}$$

$$= \textbf{413.73 psi}$$

For **Redlich-Kwong EOS** we have the parameters from Table D.1

$$T_r = T/T_c = (100 + 459.67) \,/\, 620.1 = 0.90255$$

$$b = 0.08664 \frac{RT_c}{P_c} = 0.08664 \times \frac{21.29 \times 620.1}{711 \times 144} = 0.011\ 172 \text{ ft}^3/\text{lbm},$$

$$a = 0.42748\ T_r^{-1/2} \frac{R^2 T_c^2}{P_c} = 0.42748 \times \frac{21.29^2 \times 620.1^2}{0.90255^{1/2} \times 711 \times 144^2}$$

$$= 5.319\ 372 \text{ psi (ft}^3/\text{lbm)}^2$$

The equation is:

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

$$= \frac{21.29 \times 559.67 \,/\, 144}{0.2 - 0.011\ 172} - \frac{5.319\ 372}{0.2^2 + 0.011\ 172 \times 0.2}$$

$$= \ \textbf{312 psia}$$

From Table F.9.2 we see it is around 300 psia.