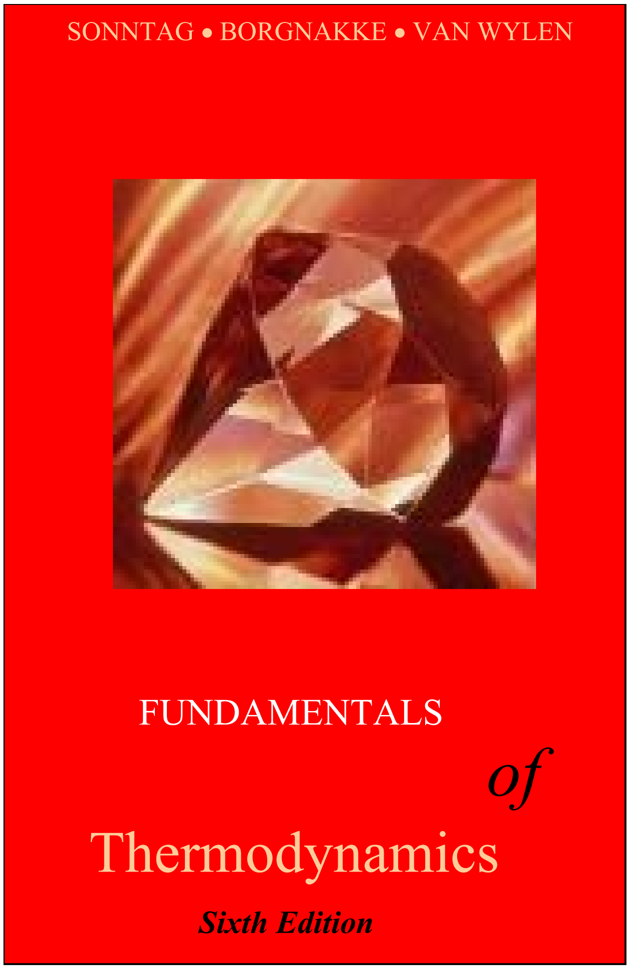
SOLUTION MANUAL
ENGLISH UNIT PROBLEMS
CHAPTER 3



CONTENT CHAPTER 3

Correspondence Table

CHAPTER 3 6th edition Sonntag/Borgnakke/Wylen

The set of problems have a correspondence to the 5th edition Fundamentals of Thermodynamics as:

Problems 3.1 through 3.20 are all new

New	5th	New	5th	New	5th
21	new	57	46	93	30 mod
22	2	58	48	94	31 mod
23	1	59	39 mod	95	32
24		60	57	96	new
25	3	61	51	97	60
26	new	62	new	98	55
27	4	63	new	99	new
28	28 mod	64	5	100	59
29	new	65	new	101	53
30	23	66	22	102	54
31	28 mod	67	6	103	50
32	24	68	new	104	49
33	new	69	8	105	45
34	new	70	new	106	56
35	new	71	10	107	9
36	29	72	13	108	52
37	new	73	new	109	7
38	new	74	25	110	47
39	27 mod	75	new	111	11
40	new	76	new	112	12
41	37	77	new	113	16
42	41	78	17	114	38
43	new	79	14	115	34
44	new	80	19	116	new
45	new	81	33	117	new
46	new	82	new	118	new
47	36	83	new	119	new
48	new	84	new	120	new
49	58	85	new	121	new
50	35	86	20	122	new
51	42	87	new	123	new
52	new	88	21	124	new
53	43	89	18	125	new
54	new	90	26 mod	126	86
55	40	91	16 mod	127	87
56	44	92	30 mod		

The English unit problem correspondence is

New	5th Ed.	SI
128	new	5
129	new	7
130	new	9
131	new	11
132	new	17
133	new	23
134	61E	27
135	68E a-c	30
136	68E d-f	30
137	new	40
138	70E	36
139	73E	47
140	74E	41
141	new	44
142	76E	51

New	5th Ed.	SI
143	77E	53
144	new	62
145	79E	58
146	62E	69
147	new	65
148	69E c+d 70E d	-
149	72E	81
150	64E	113
151	new	74
152	81E	49
153	new	99
154	71E	95
155	80E	61
156	83E	106
157	65E	89
158	66E	-

The Computer, design and open-ended problem correspondence is

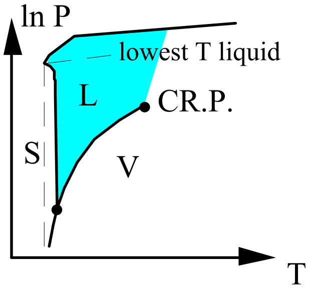
New	5th	New	5th	New	5th
159	new	163	90	167	94
160	new	164	91	168	95
161	88	165	92		
162	89	166	93		

mod indicates a modification from the previous problem that changes the solution but otherwise is the same type problem.

Concept-Study Guide Problems

3.1

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



Look at the phase diagram in Fig. 3.7. 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^{o}C.

T ≈ 255 K ≈ - 18°C

3.2

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

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 $v_f = 0.00100$ m^3/kg

From Table B.1.5 $v_i = 0.0010908$ m^3/kg

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

Liquid water that seeps into cracks or other confined spaces and then freezes will expand and widen the cracks. This is what destroys any pourous material exposed to the weather on buildings, roads and mountains.

3.3

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. 3.7. 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.

3.4

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.

3.5

Some tools should be cleaned in water at a least 150^{o}C. How high a P is needed?

Solution:

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

Table B.1.1: 150^{o}C $\quad P_{sat}$ = 475.9 kPa.

3.6

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.

3.7

If I have 1 L ammonia at room pressure and temperature (100 kPa, 20^{o}C) how much mass is that?

Ammonia Tables B.2:

B.2.1 P_{sat} = 857.5 kPa at 20^{o}C so superheated vapor.

B.2.2 v = 1.4153 m^3/kg under subheading 100 kPa

$$m = \frac{V}{v} = \frac{0.001\ m^3}{1.4153\ m^3/kg} = \mathbf{0.000\ 706\ kg = 0.706\ g}$$

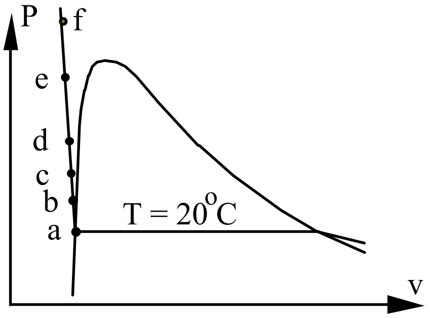
3.8

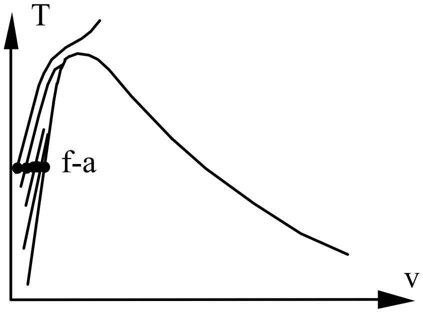
How much is the change in liquid specific volume for water at 20^{o}C as you move up from state i towards state j in figure 3.12 reaching 15 000 kPa?

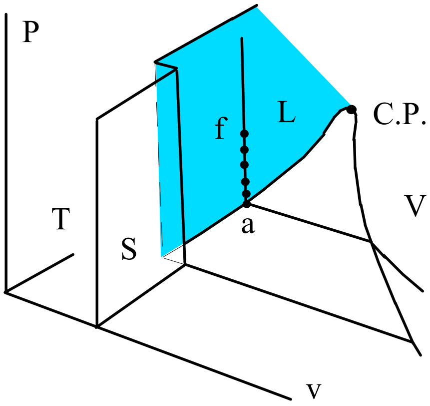
State “i”, here “a”, is saturated liquid and up is then compressed liquid states

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.







3.9

For water at 100 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: $v_f = 0.001\ 043\ \mathrm{m^3/kg}$, $v_g = 1.6940\ \mathrm{m^3/kg}$

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

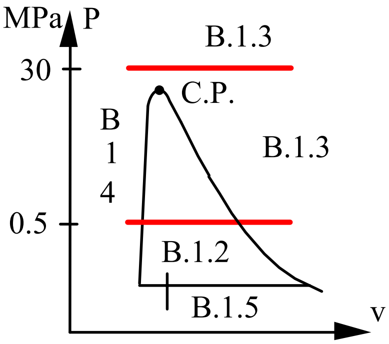
$$\text{Fraction} = \frac{V_g}{V} = \frac{V_g}{V_g + V_f} = \frac{x\ m\ v_g}{x\ m\ v_g + (1 - x) m\ v_f}$$

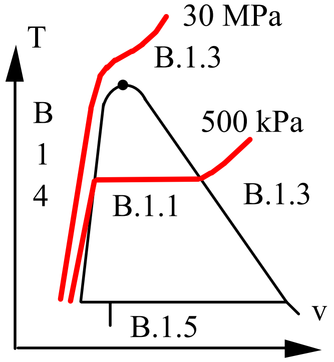
$$= \frac{0.1 \times 1.694}{0.1 \times 1.694 + 0.9 \times 0.001043} = \frac{0.1694}{0.17034} = \mathbf{0.9945}$$

Notice that the liquid volume is only about 0.5% of the total. We could also have found the overall $v = v_f + x v_{fg}$ and then $V = m\ v$.

3.10

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.



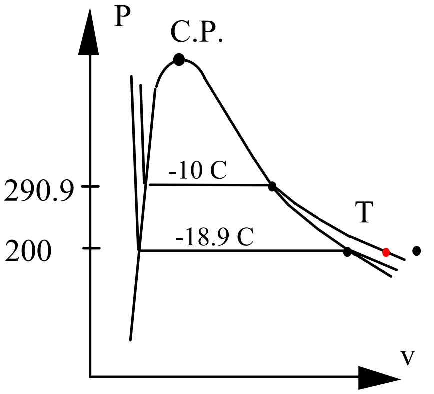


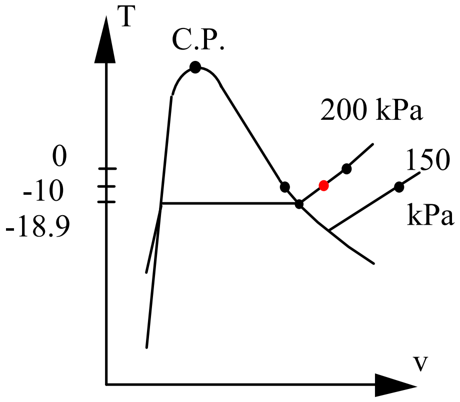
The 30 MPa line in Table B.1.4 starts at 0°C and table ends at 380°C, the line is continued in Table B.1.3 starting at 375°C and table ends at 1300°C.

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

3.11

Locate the state of ammonia at 200 kPa, -10^{o}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





3.12

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.

3.13

Water at 120°C with a quality of 25% has its temperature raised 20°C in a constant volume process. What is the new quality and pressure?

Solution:

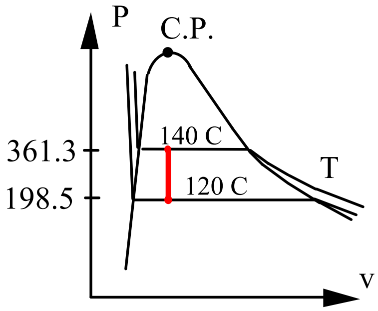
State 1 from Table B.1.1 at 120°C

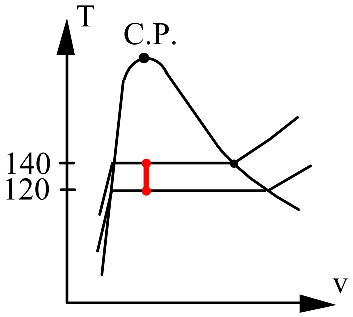
$$v = v_f + x\, v_{fg} = 0.001060 + 0.25 \times 0.8908 = 0.22376\ \mathrm{m^3/kg}$$

State 2 has same v at 140°C also from Table B.1.1

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.22376 - 0.00108}{0.50777} = \mathbf{0.4385}$$

$$P = P_{sat} = \mathbf{361.3\ kPa}$$





3.14

Water at 200 kPa with a quality of 25% has its temperature raised 20°C in a constant pressure process. What is the new quality and volume?

Solution:

State 1 from Table B.1.2 at 200 kPa

$$v = v_f + x\, v_{fg} = 0.001061 + 0.25 \times 0.88467 = 0.22223 \text{ m}^3\text{/kg}$$

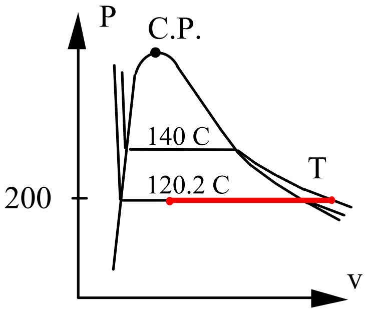
State 2 has same P from Table B.1.2 at 200 kPa

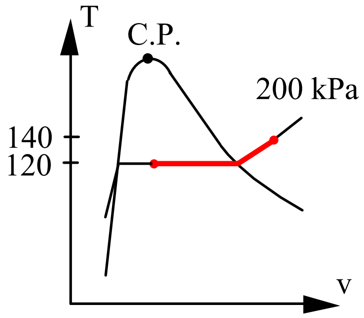
$$T_2 = T_{sat} + 20 = 120.23 + 20 = 140.23^{o}\text{C}$$

so state is superheated vapor

x = undefined

$$v = 0.88573 + (0.95964 - 0.88573)\frac{20}{150 - 120.23} = \mathbf{0.9354\ m^3/kg}$$





3.15

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.

3.16

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

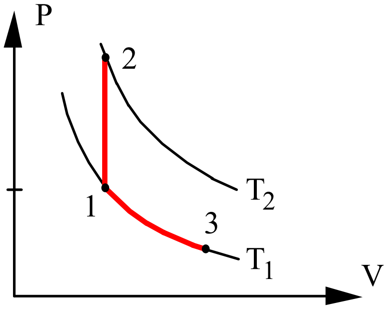
Ideal gas law: $PV = mRT$

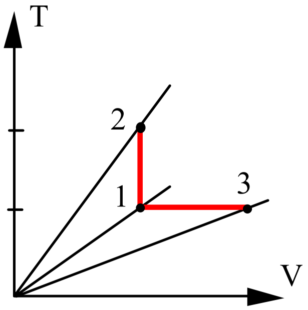
State 2: $P_2V = mRT_2 = mR2T_1 = 2P_1V \Rightarrow P_2 = 2P_1$

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%**





3.17

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

The gas constant for a substance can be found from the universal gas constant from the front inside cover and the molecular weight from Table A.2

Argon: $R = \frac{\bar{R}}{M} = \frac{8.3145}{39.948} = \mathbf{0.2081\ kJ/kg\ K}$

Hydrogen: $R = \frac{\bar{R}}{M} = \frac{8.3145}{2.016} = \mathbf{4.1243\ kJ/kg\ K}$

3.18

How close to ideal gas behavior (find Z) is ammonia at saturated vapor, 100 kPa? How about saturated vapor at 2000 kPa?

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

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

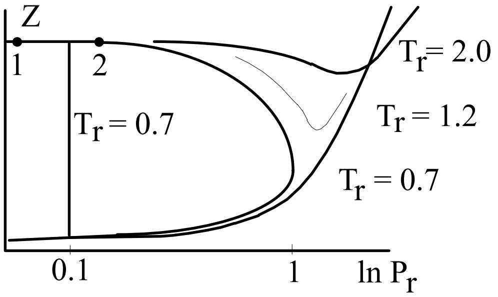
Table A.5: $R = 0.4882\ kJ/kg\ K$

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

$$Z_1 = \frac{P_1v_1}{RT_1} = \frac{100 \times 1.1381}{0.4882 \times (273.15 - 33.6)} = 0.973$$

$$Z_2 = \frac{P_2v_2}{RT_2} = \frac{2000 \times 0.06444}{0.4882 \times (273.15 + 49.37)} = 0.8185$$

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



3.19

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

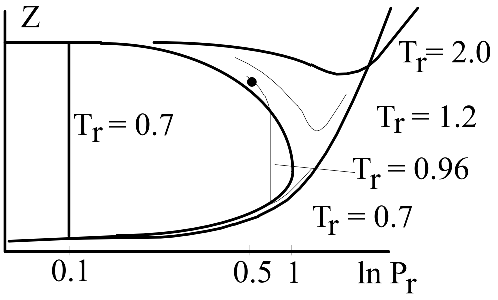
Table A.5: $R = 0.2964$ kJ/kg K

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: $Z = 0.76$

$$V = \frac{mZRT}{P} = \frac{2 \times 0.76 \times 0.2964 \times 270}{2500} = \mathbf{0.0487\ m^3}$$



3.20

With $T_r = 0.85$ and a quality of 0.6 find the compressibility factor using Fig. D.1

For the saturated states we will use Table D.4 instead of the figure. There we can see at $T_r = 0.85$

$$Z_f = 0.062, \qquad Z_g = 0.747$$

$$Z = (1 - x)\, Z_f + xZ_g = (1 - 0.6)\, 0.062 + 0.6 \times 0.747 = \mathbf{0.473}$$

Phase Diagrams, Triple and Critical Points

3.21

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: $P_c = \mathbf{7.38\ MPa}$, $T_c = 304$ K, $v_c = 0.00212\ m^3/kg$

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

C_2H_5OH:

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

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

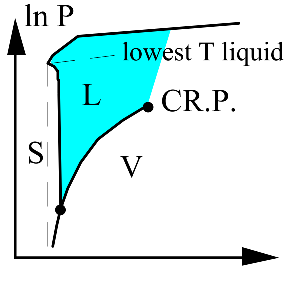
3.22

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. 3.6, saturated ice III to liquid phase boundary is at

T ≈ 263K ≈ - 10°C and
P ≈ 2100 MPa



3.23

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:

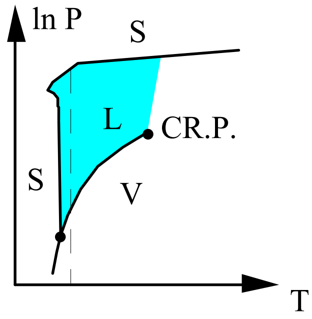
The phases can be seen in Fig. 3.6, a sketch of which is shown to the right.

$T = 27\ ^\circ C = 300\ K$

From Fig. 3.6:

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

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



$0 < P < 4\ kPa$ VAPOR

$0.004\ MPa < P < 1000\ MPa$ LIQUID

$P > 1000\ MPa$ SOLID(ICE)

3.24

What is the lowest temperature in Kelvins for which you can see metal as a liquid if the metal is *a.* silver *b.* copper

Solution:

Assume the two substances have a phase diagram similar to Fig. 3.6, then we can see the triple point data in Table 3.2

$T_a = 961^oC = 1234$ K

$T_b = 1083^oC = 1356$ K

3.25

If density of ice is 920 kg/m^3, find the pressure at the bottom of a 1000 m thick ice cap on the north pole. What is the melting temperature at that pressure?

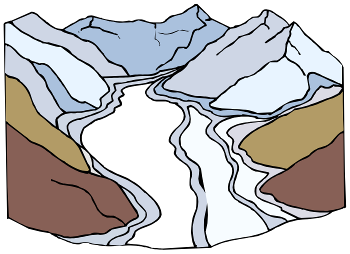
Solution:

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

$\Delta P = \rho g H = 920 \text{ kg/m}^3 \times 9.80665 \text{ m/s}^2 \times 1000 = 9022\,118$ Pa

$P = P_o + \Delta P = 101.325 + 9022 = 9123$ kPa

See figure 3.6 liquid solid interphase => **$T_{LS} = -1$°C**



3.26

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?

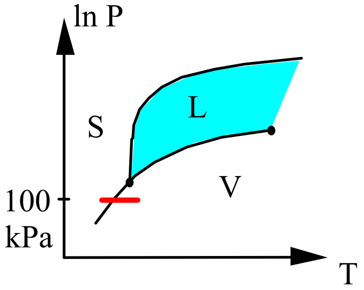
Solution:

The phase boundaries are shown in Figure 3.6

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.



3.27

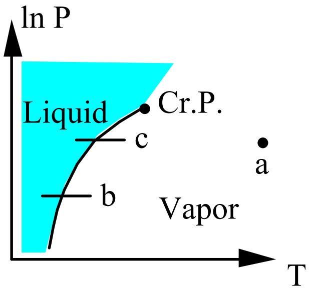
A substance is at 2 MPa, 17°C in a rigid tank. Using only the critical properties can the phase of the mass be determined if the substance is nitrogen, water or propane ?

Solution:

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

a)	Nitrogen	N_2	: 3.39 MPa	126.2 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:



N_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

3.28

Give the phase for the following states.

Solution:

a. CO_2 $T = 267^{\circ}C$ $P = 0.5$ MPa Table A.2

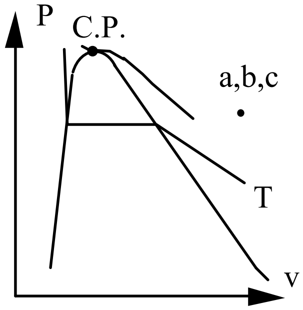
superheated vapor assume ideal gas Table A.5

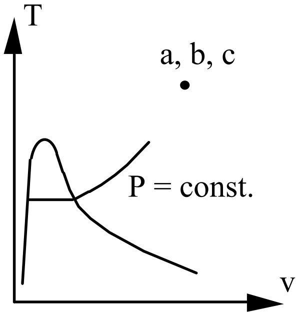
b. Air $T = 20^{\circ}C$ $P = 200$ kPa Table A.2

superheated vapor assume ideal gas Table A.5

c. NH_3 $T = 170^{\circ}C$ $P = 600$ kPa Table B.2.2 or A.2

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





3.29

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-12	0°C, 350 kPa

Solution:

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

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

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

$100^\circ C < T_{sat}$ then it is subcooled liquid = compressed liquid

b) Ammonia NH_3 :

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

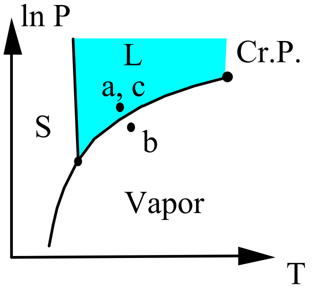
Superheated vapor

c) R-12

Table B.3.1: $P > P_{sat}(0\ ^\circ C) = 309$ kPa

Compressed liquid.

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



3.30

Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

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

$v_f = 0.001452$; $v_g = 0.01803$ m^3/kg,

=> $v_f < v < v_g$ => so mixture of liquid and vapor.

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

c. 200°C, 0.1 m^3/kg: look in B.1.1

$v_f = 0.001156$ m^3/kg ; $v_g = 0.12736$ m^3/kg,

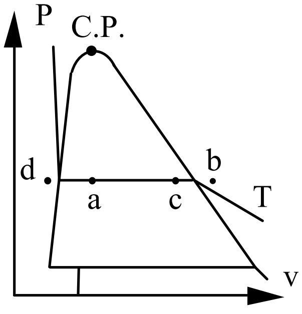
=> $v_f < v < v_g$ => so mixture of liquid and vapor.

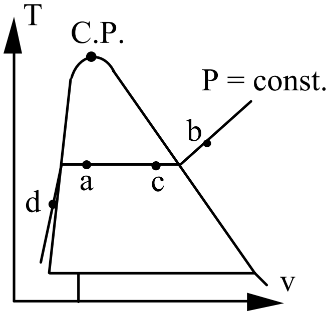
d. 10 kPa, 10°C : Only one of the two look-ups is needed

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

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





3.31

Give the phase for the following states.

Solution:

a. H_2O $T = 275^\circ C$ $P = 5$ MPa Table B.1.1 **or** B.1.2

B.1.1 $P_{sat} = 5.94$ MPa => **superheated vapor**

B.1.2 $T_{sat} = 264^\circ C$ => **superheated vapor**

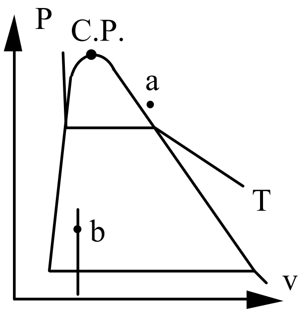
b. H_2O $T = -2^\circ C$ $P = 100$ kPa Table B.1.1 $T < T_{triple\ point}$

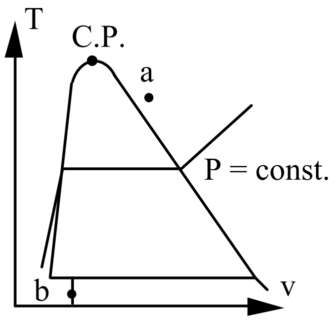
Table B.1.5 at $-2^\circ C$ $P_{sat} = 0.518$ kPa

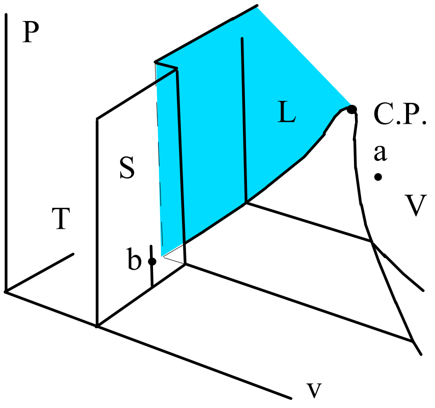
since $P > P_{sat}$ => **compressed solid**

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

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







3.32

Determine whether refrigerant R-22 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

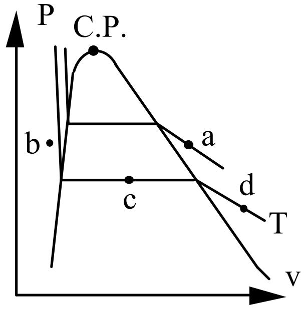
a. 50°C, 0.05 m^3/kg From table B.4.1 at 50°C $v_g = 0.01167\ m^3/kg$
since $v > v_g$ we have **superheated vapor**

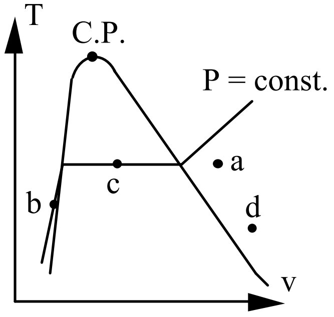
b. 1.0 MPa, 20°C From table B.4.1 at 20°C $P_g = 909.9$ kPa
since $P > P_g$ we have **compressed liquid**

c. 0.1 MPa, 0.1 m^3/kg From table B.4.1 at 0.1 MPa (use 101 kPa)
$v_f = 0.0007$ and $v_g = 0.2126\ m^3/kg$
as $v_f < v < v_g$ we have a **mixture of liquid & vapor**

d −20°C, 200 kPa **superheated vapor**, $P < P_g = 244.8$ kPa at -20°C

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





General Tables

3.33

Fill out the following table for substance water:

Solution:

	P [kPa]	T [^oC]	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

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

$$T = T_{sat} = 151.86^oC$$

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 $T > T_{sat} = 195^oC$

Table B.1.3 subtable for 1400 kPa gives the state properties

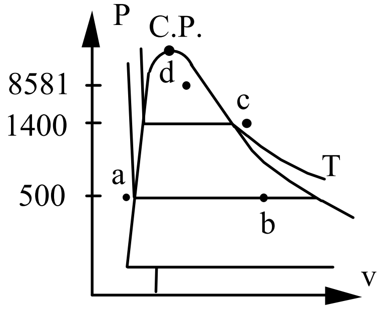
d) Table B.1.1 since quality is given it is two-phase

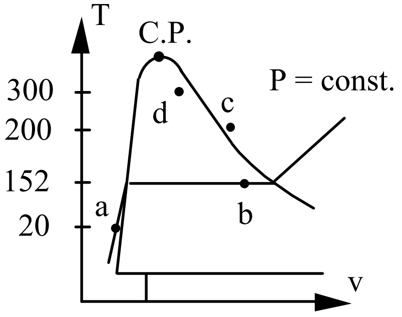
$$v = v_f + x \times v_{fg} = 0.001404 + 0.8 \times 0.02027 = 0.01762 \text{ m}^3/\text{kg}$$

3.34

Place the four states a-d listed in Problem 3.33 as labeled dots in a sketch of the P-v and T-v diagrams.

Solution:





3.35

Determine the phase and the specific volume for ammonia at these states using the Appendix B table.

a. $-10^{o}C$, 150 kPa
b. $20^{o}C$, 100 kPa
c. $60^{o}C$, quality 25%

Solution:

Ammonia, NH_3, properties from Table B.2

a)

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

Superheated vapor B.2.2 $v =$ **$0.8336\ m^3/kg$**

b)

Table B.2.1 at given T: $P_{sat} = 847.5$ kPa so $P < P_{sat}$

Superheated vapor B.2.2 $v =$ **$1.4153\ m^3/kg$**

c)

Table B.2.1 enter with T (this is two-phase L + V)

$v = v_f + x\ v_{fg} = 0.001834 + x \times 0.04697 =$ **$0.01358\ m^3/kg$**

3.36

Give the phase and the specific volume.

Solution:

a. R-22 $T = -25^\circ C$ $P = 100$ kPa

Table B.4.1 at given T: $P_{sat} = 201$ kPa so $P < P_{sat}$ =>

sup. vap. B.4.2 $v \cong (0.22675 + 0.23706)/2 = \mathbf{0.2319\ m^3/kg}$

b. R-22 $T = -25^\circ C$ $P = 300$ kPa

Table B.4.1 at given T: $P_{sat} = 201$ kPa so

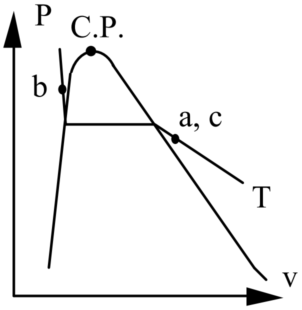
compr. liq. as $P > P_{sat}$ $v \cong v_f = \mathbf{0.000733\ m^3/kg}$

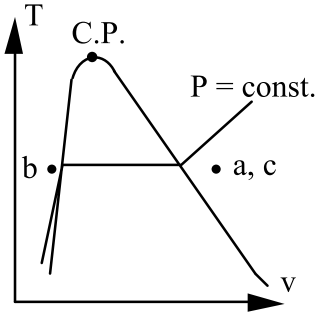
c. R-12 $T = 5^\circ C$ $P = 200$ kPa

Table B.3.1 at given T: $P_{sat} = 362.6$ kPa so $P < P_{sat}$

sup. vap. B.3.2 $v \cong (0.08861 + 0.09255)/2 = \mathbf{0.09058\ m^3/kg}$

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





3.37

Fill out the following table for substance ammonia:

Solution:

	P [kPa]	T [^oC]	v [m^3/kg]	x
a)	**1200**	50	0.1185	**Undefined**
b)	**2033**	50	**0.0326**	0.5

a) B.2.1 $v > v_g$ => superheated vapor Look in B.2.2

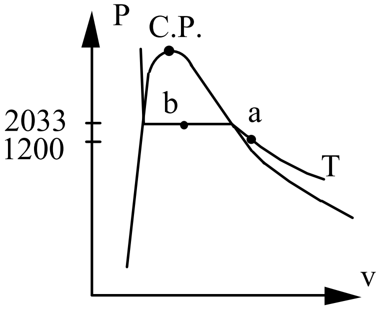
b) B.2.1 $P = P_{sat} = 2033$ kPa

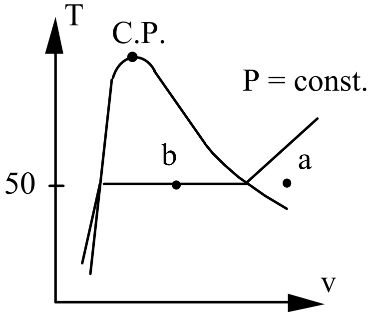
$v = v_f + x\, v_{fg} = 0.001777 + 0.5 \times 0.06159 = 0.0326\ m^3/kg$

3.38

Place the two states a-b listed in Problem 3.37 as labeled dots in a sketch of the P-v and T-v diagrams.

Solution:





3.39

Calculate the following specific volumes

a. R-134a: 50°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.3.1 or 3.2

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

a. R-134a: 50°C, 80% quality in Table B.5.1

$$v = 0.000908 + x \times 0.01422 = 0.01228\ m^3/kg$$

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

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

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

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

3.40

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

a. R-134a $T = -20^oC$, $P = 150$ kPa

b. R-134a $P = 300$ kPa, $v = 0.072$ m^3/kg

c. CH_4 $T = 155$ K, $v = 0.04$ m^3/kg

d. CH_4 $T = 350$ K, $v = 0.25$ m^3/kg

Solution:

a) B.5.1 $P > P_{sat} = 133.7 \text{ kPa} \Rightarrow$ compressed liquid

$v \sim v_f = 0.000738 \; m^3/kg$

x = undefined

b) B.5.2 $v > v_g$ at 300 kPa $\Rightarrow$ superheated vapor

$$T = 10 + (20\text{-}10) \left(\frac{0.072 - 0.07111}{0.07441 - 0.07111}\right) = 12.7°C$$

x = undefined

c) B.7.1 $v > v_g = 0.04892 \; m^3/kg$ 2-phase

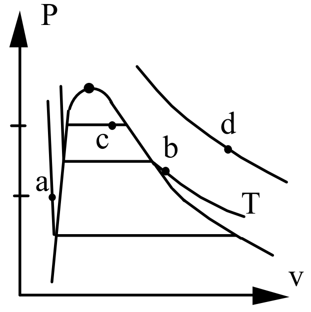
$$x = \frac{v - v_f}{v_{fg}} = \frac{0.04\text{-}0.002877}{0.04605} = 0.806$$

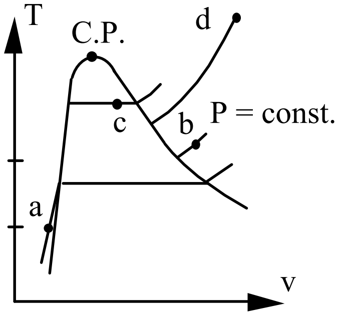
$P = P_{sat} = 1295.6$ kPa

d) B.7.1 $T > T_c$ and $v >> v_c$ $\Rightarrow$ superheated vapor B.7.2

located between 600 & 800 kPa

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





3.41

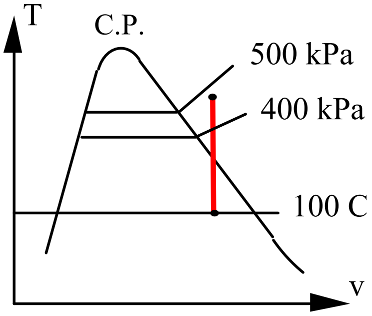
A sealed rigid vessel has volume of 1 m^3 and contains 2 kg of water at 100°C. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 200°C?

Solution:

Process: v = V/m = constant

State 1: $v_1 = 1/2 = 0.5\ m^3/kg$
from Table B.1.1
it is 2-phase

State 2: 200°C, 0.5 m^3/kg
Table B.1.3 between 400
and 500 kPa so interpolate



$$P \cong 400 + \frac{0.5-0.53422}{0.42492-0.53422} \times (500-400) = \mathbf{431.3\ kPa}$$

3.42

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?

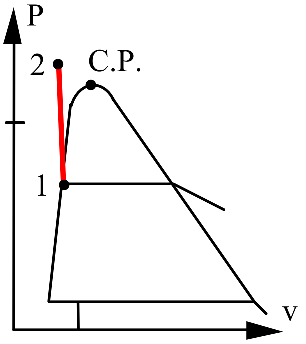
Solution:

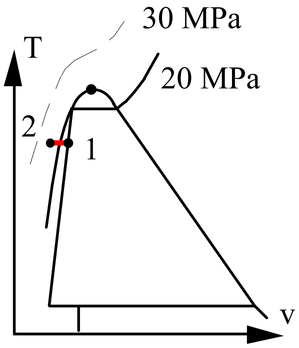
State 1: $T = 60°C$, $x = 0.0$; Table B.1.1: $v = 0.001017\ m^3/kg$

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**





3.43

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 if the temperature is changed to a) 200 °C and b) 100 °C.

Solution:

State 1: (200 kPa, x = 1) in B.1.2: $v_1 = v_g$ (200 kPa) = $\mathbf{0.8857\ m^3/kg}$

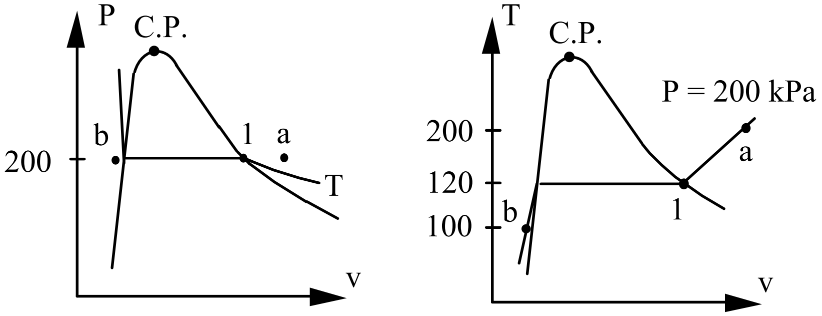
State a: (200 kPa, 200 °C) B.1.3: $v_a = 1.083\ m^3/kg$

State b: (200 kPa, 100 °C) B.1.1: $v_b = 0.001044\ m^3/kg$

As the piston height is proportional to the volume we get

$$h_a = h_1 (v_a / v_1) = 0.1 \times (1.0803 / 0.8857) = \mathbf{0.12\ m}$$

$$h_b = h_1 (v_b / v_1) = 0.1 \times (0.001044 / 0.8857) = \mathbf{0.00011\ m}$$



3.44

You want a pot of water to boil at 105°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°C : $P_{sat} = 120.8$ kPa

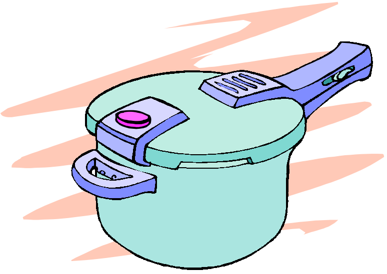
$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} 0.15^2 = 0.01767 \text{ m}^2$$

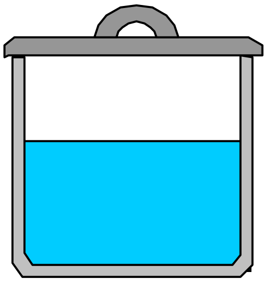
$$F_{net} = (P_{sat} - P_{atm})\, A = (120.8 - 101) \text{ kPa} \times 0.01767 \text{ m}^2$$
$$= 0.3498 \text{ kN} = 350 \text{ N}$$

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

$$m_{lid} = F_{net}/g = \frac{350}{9.807} = \mathbf{35.7\ kg}$$

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





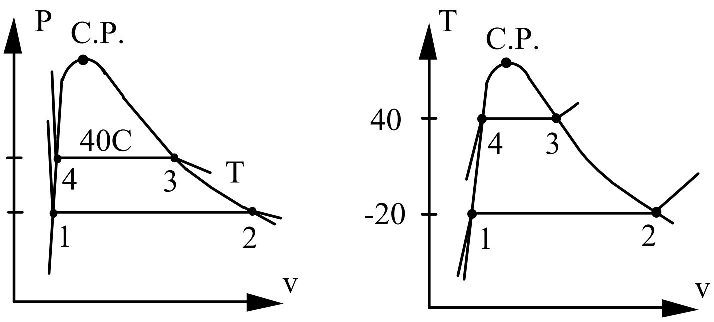
3.45

In your refrigerator the working substance evaporates from liquid to vapor at -20 °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 +40 °C. For each location find the pressure and the change in specific volume (v) if

a) the substance is R-12
b) 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	$\Delta v = v_{fg}$
R-12	B.3.1	40 °C	961	0.017
R-12	B.3.1	-20 °C	151	0.108
Ammonia	B.2.1	40 °C	1555	0.0814
Ammonia	B.2.1	-20 °C	190	0.622



3.46

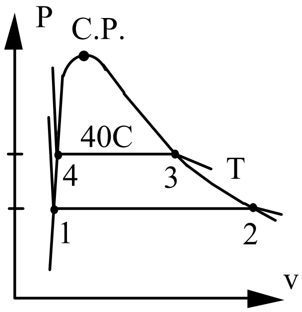
In your refrigerator the working substance evaporates from liquid to vapor at -20 °C inside a pipe around the cold section. Outside (on the back or below) is a black grille inside which the working substance condenses from vapor to liquid at +40 °C. For each location find the pressure and the change in specific volume (v) if:

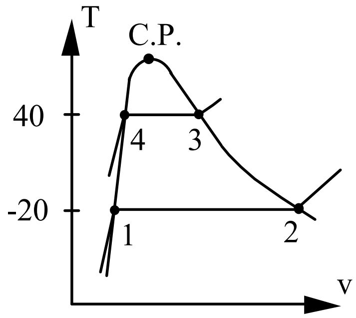
a) the substance is R-134a b) the substance is R-22

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	$\Delta v = v_{fg}$
R-134a	B.5.1	40 °C	1017	0.019
R-134a	B.5.1	-20 °C	134	0.146
R-22	B.4.1	40 °C	1534	0.0143
R-22	B.4.1	-20 °C	245	0.092





3.47

A water storage tank contains liquid and vapor in equilibrium at 110°C. The distance from the bottom of the tank to the liquid level is 8 m. What is the absolute pressure at the bottom of the tank?

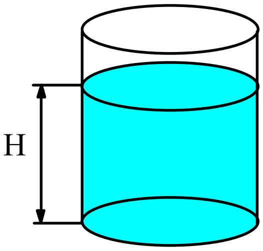
Solution:

Saturated conditions from Table B.1.1: $P_{sat} = 143.3$ kPa

$v_f = 0.001052\ m^3/kg$;

$$\Delta P = \frac{gh}{v_f} = \frac{9.807 \times 8}{0.001052} = 74\ 578\ \text{Pa} = 74.578\ \text{kPa}$$

$$P_{bottom} = P_{top} + \Delta P = 143.3 + 74.578 = \mathbf{217.88\ kPa}$$



3.48

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 $v_1 = v_g (200 \text{ kPa}) = 0.8857 \text{ m}^3/\text{kg}$, $T_1 = 120.2°C$

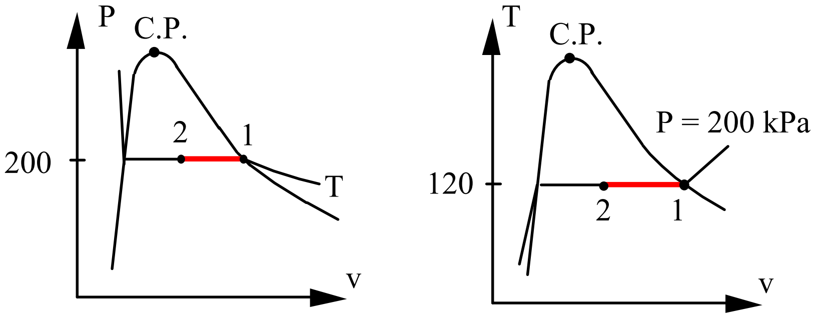
Process: P = constant = 200 kPa

State 2: P, $v_2 = v_1/2 = 0.44285 \text{ m}^3/\text{kg}$

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

Height is proportional to volume

$h_2 = h_1 \times v_2/v_1 = 0.1 \times 0.5 = \mathbf{0.05m}$

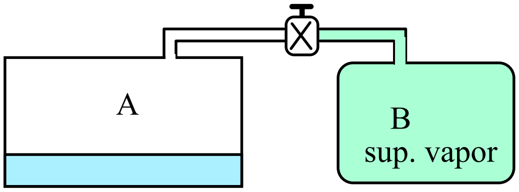


3.49

Two tanks are connected as shown in Fig. P3.49, 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 $v_B = 0.6173\ m^3/kg$

$$\Rightarrow V_B = m_B v_B = 3.5 \times 0.6173 = 2.1606\ m^3$$

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

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

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

3.50

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

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.

$$\Rightarrow \quad v \cong 0.03333 + \frac{243.15\text{-}225}{250\text{-}225} \times (0.03896 - 0.03333) = 0.03742\ m^3/kg$$

$$m = V/v = 2/0.03742 = \mathbf{53.45\ kg}$$

Ideal gas assumption

$$v = RT/P = 0.51835 \times 243.15/3000 = 0.042\ \ m^3/kg$$

$$m = V/v = 2/0.042 = 47.62\ kg$$

Error: 5.83 kg **10.9% too small**

3.51

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?

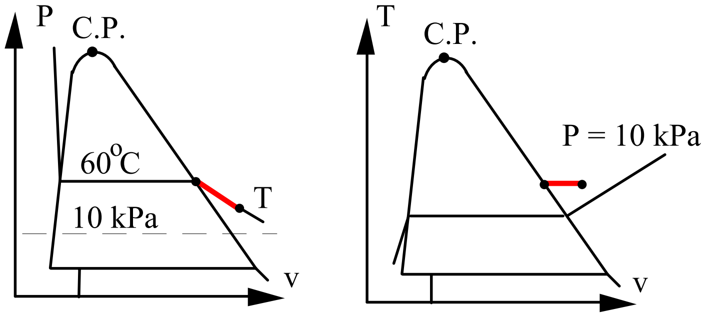
Solution:

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

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

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

$$P \cong 19.941 + (10 - 19.941)\,\frac{8.4378 - 7.6707}{15.3345 - 7.6707} = \mathbf{18.9\ kPa}$$



Comment: T,v ⇒ P = 18 kPa (software) v is not linear in P, more like 1/P, so the linear interpolation in P is not very accurate.

3.52

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 heated to occupy twice the original volume?

Solution:

From B.1.2, $v_1 = 0.8857\ \mathrm{m^3/kg}$

2: From B.1.3., $P_2 = P_1,\ v_2 = 2v_1 = 2 \times 0.8857 = 1.7714\ \mathrm{m^3/kg}$

Since the cross sectional area is constant the height is proportional to volume

$$h_2 = h_1\, v_2/v_1 = 2h_1 = \mathbf{0.2\ m}$$

Interpolate for the temperature

$$T_2 = 400 + 100\,\frac{1.7714 - 1.5493}{1.78139 - 1.5493} \approx \mathbf{496°C}$$

3.53

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?

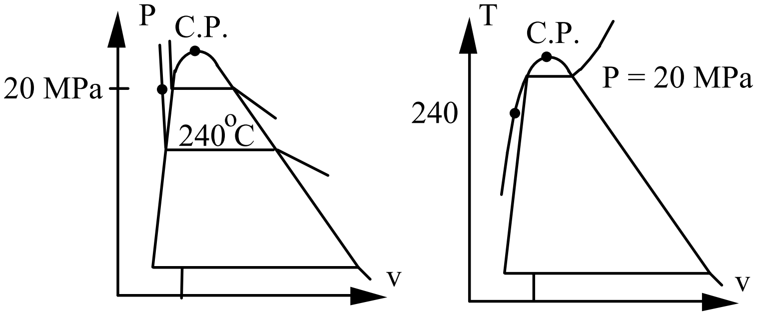
Solution:

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

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

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

$v_{f\,(20\text{ MPa})} = 0.002036 \text{ m}^3/\text{kg} \Rightarrow \dot{m} = 24.56 \text{ kg/s}$ **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.

3.54

Saturated vapor R-134a at 50°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: $v_1 = v_g = 0.01512\ \text{m}^3/\text{kg}$, $P_1 = P_{sat} =$ **1318 Kpa**

2: $v_2 = 2v_1 = 0.03024\ \text{m}^3/\text{kg}$ **superheated vapor**

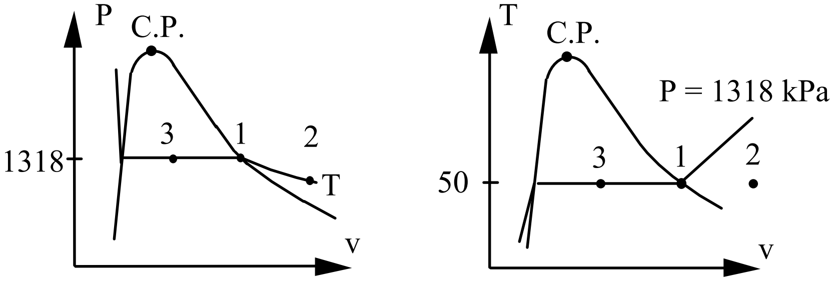
Interpolate between 600 kPa and 800 kPa

$$P_2 = 600 + 200 \times \frac{0.03024 - 0.03974}{0.02861 - 0.03974} = \mathbf{771\ kPa}$$

3: $v_3 = v_1/2 = 0.00756\ \text{m}^3/\text{kg} < v_g$: two phase

$$x_3 = \frac{v_3 - v_f}{v_{fg}} = \frac{0.00756 - 0.000908}{0.01422} = 0.4678$$

$P_3 = P_{sat} =$ **1318 kPa**



3.55

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 $v = \text{constant} = v_1$

$$v_1 = 0.002439 + 0.25 \times 0.30367 = 0.078366 \text{ m}^3/\text{kg}$$

We then also see that $v_1 > v_c = 0.00615 \text{ m}^3/\text{kg}$

All single phase when $v = v_g \Rightarrow T \cong 145$ K

$\Delta t = \Delta T/(5°\text{C/h}) \cong (145 - 120) / 5 =$ **5 hours** $P = P_{sat} =$ **824 kPa**

3.56

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:

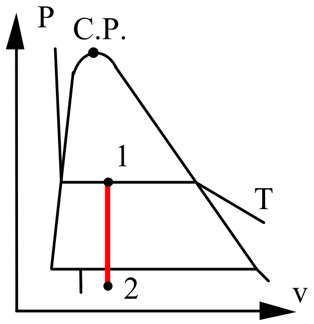
Constant volume and mass $\Rightarrow$ $v_1 = v_2 = V/m$

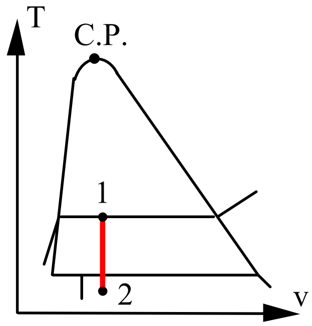
From Table B.1.2: $v_1 = 0.001093 + 0.25 \times 0.3738 = 0.094543$

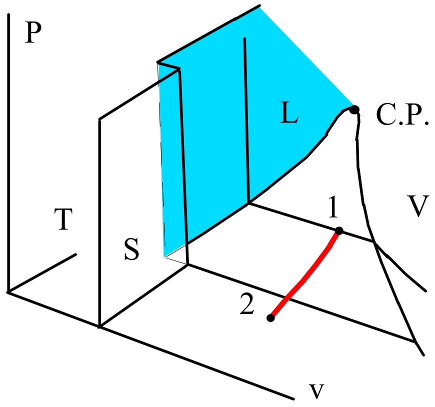
From Table B.1.5: $v_2 = 0.0010891 + x_2 \times 446.756 = v_1 = 0.094543$

$\Rightarrow$ $x_2 = 0.0002$ mass fraction vapor

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







3.57

Saturated (liquid + vapor) ammonia at 60°C is contained in a rigid steel tank. It is used in an experiment, where it should pass through the critical point when the system is heated. What should the initial mass fraction of liquid be?

Solution:

Process: Constant mass and volume, $v = C$

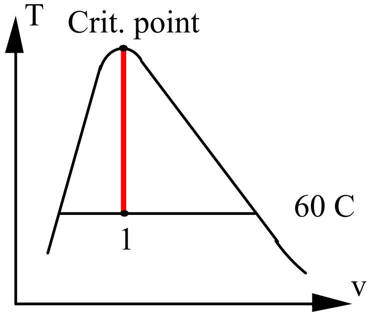
From table B.2.1:

$v_2 = v_c = 0.004255\ m^3/kg$

$v_1 = 0.001834 + x_1 \times 0.04697 = 0.004255$

=> $x_1 = 0.01515$

liquid mass fraction = $1 - x_1 =$ **0.948**

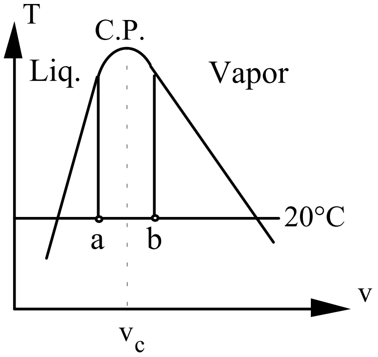


3.58

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 $\quad v_2 = v_1 = \frac{V}{m} = \frac{0.015 \text{ m}^3}{6 \text{ kg}} = 0.0025 \text{ m}^3\text{/kg}$



A.2: $v_c = 0.00454 \text{ m}^3\text{/kg} > v_1$

eventually reaches sat. liquid.

⇒ **level rises to top**

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

then it will reach saturated vapor.

⇒ **level falls**

3.59

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)

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

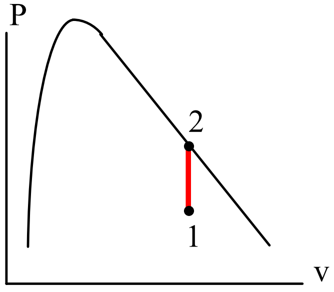
$$m_{tot} = \mathbf{152\ 227\ kg}, \quad x = m_{vap} / m_{tot} = \mathbf{4.72 \times 10^{-4}}$$

3.60

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.



State 2 is saturated vapor, from table B.5.1

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

State 1: same specific volume as state 2

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

$v_1 = 0.000794 + x_1 \times 0.048658$

$\Rightarrow\ x_1 = 0.2945$

$m = V/v_1 = 2/0.015124 = 132.24$ kg; $\quad m_{liq} = (1 - x_1)m = \mathbf{93.295\ kg}$

3.61

A pressure cooker (closed tank) contains water at 100°C with the liquid volume being 1/10 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:

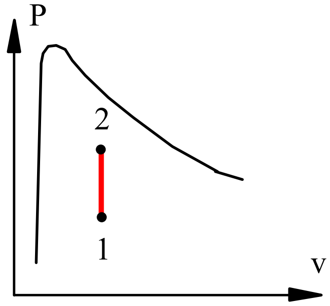
State 1: $V_f = m_f v_f = V_g/10 = m_g v_g/10$;

Table B.1.1: $v_f = 0.001044 \text{ m}^3/\text{kg}$, $v_g = 1.6729 \text{ m}^3/\text{kg}$

$$x_1 = \frac{m_g}{m_g + m_f} = \frac{10\, m_f v_f / v_g}{m_f + 10\, m_f v_f / v_g} = \frac{10\, v_f}{10\, v_f + v_g} = \frac{0.01044}{0.01044 + 1.6729} = 0.0062$$

$v_1 = 0.001044 + 0.0062 \times 1.67185 = 0.01141 \text{ m}^3/\text{kg}$

State 2: $v_2 = v_1 = 0.01141 \text{ m}^3/\text{kg} < v_g(2\text{MPa})$ from B.1.2 so two-phase



At state 2: $v_2 = v_f + x_2\, v_{fg}$

$0.01141 = 0.001177 + x_2 \times 0.09845$

=> $x_2 = 0.104$

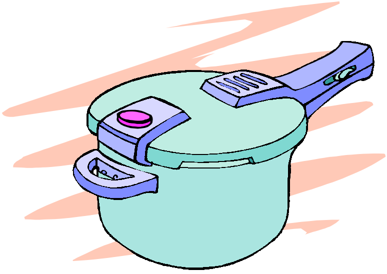
More vapor at final state

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

3.62

A pressure cooker has the lid screwed on tight. A small opening with $A = 5\ \text{mm}^2$ 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^oC with an outside atmosphere at 101.3 kPa?

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



$$F = mg = \Delta P \times A$$

$$m = \Delta P \times A/g$$

$$= \frac{(198.5\text{-}101.3)\times 1000\times 5\times 10^{-6}}{9.807}$$

$$= 0.0496\ \text{kg} = \mathbf{50\ g}$$

3.63

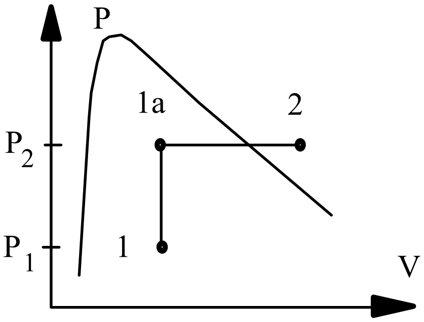
Ammonia at 10 °C and mass 0.1 kg is in a piston cylinder with an initial volume of 1 m^3. The piston initially resting on the stops has a mass such that a pressure of 900 kPa will float it. Now the ammonia is slowly heated to 50°C. Find the final pressure and volume.

Solution:

C.V. Ammonia, constant mass.

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

State 1: $T = 10\ ^\circ\text{C}$, $v_1 = \frac{V}{m} = \frac{1}{10} = 0.1\ \text{m}^3/\text{kg}$



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, $v = v_1 = 0.1\ \text{m}^3/\text{kg} < v_g$ at 900 kPa

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

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 : $v_2 = 0.16263\ \text{m}^3/\text{kg}$

$V_2 = mv_2 = \mathbf{1.6263\ m^3}$

Ideal Gas Law

3.64

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.

3.65

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?

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

$$m_{He} = \rho V = \frac{V}{v} = \frac{PV}{RT}$$

$$= \frac{100 \times 523.6}{2.0771 \times 288} = 87.5 \text{ kg}$$

$$m_{air} = \frac{PV}{RT} = \frac{100 \times 523.6}{0.287 \times 288} = 633 \text{ kg}$$

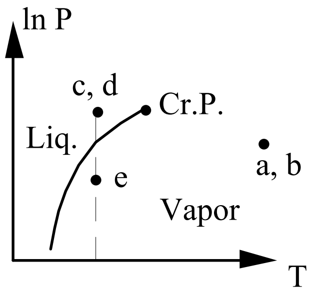
$$m_{lift} = m_{air} - m_{He} = 633\text{-}87.5 = \mathbf{545.5\ kg}$$

3.66

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)



3.67

A 1-m^3 tank is filled with a gas at room temperature 20°C and pressure 100 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 ; $P = 100$ 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) $m = \frac{PV}{RT} = \frac{100 \times 1}{0.287 \times 293.15} = \mathbf{1.189\ kg}$

b) $m = \frac{100 \times 1}{0.41195 \times 293.15} = \mathbf{0.828\ kg}$

c) $m = \frac{100 \times 1}{0.18855 \times 293.15} = \mathbf{1.809\ kg}$

3.68

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 then the final pressure?

Solution:

$$m = \frac{PV}{RT} = \frac{600 \times 1}{0.2968 \times 400} = 5.054 \text{ kg}$$

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

$$P_2 = \frac{m_2 R T_2}{V} = \frac{4.554 \times 0.2968 \times 375}{1} = \mathbf{506.9\ kPa}$$

3.69

A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 25°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

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

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

$$\Rightarrow P = \frac{1.2 \text{ kg} \times 0.1889 \text{ kJ/kg K} \times (273.15 + 25) \text{ K}}{0.031416 \text{ m}^3} = \mathbf{2152 \text{ kPa}}$$

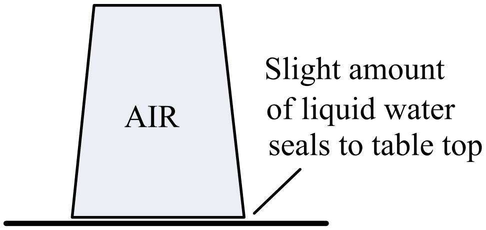
3.70

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, ?

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

$$P_2 = P_1 \frac{T_1}{T_2} = 103 \times \frac{20 + 273}{40 + 273} = \mathbf{96.4\ kPa}$$

3.71

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: $V = \frac{\pi}{6}(0.15)^3 = 0.001767 \text{ m}^3$

$$M = \frac{m\bar{R}T}{PV} = \frac{0.0025 \times 8.3145 \times 298.2}{875 \times 0.001767} = \mathbf{4.009} \approx M_{He}$$

=> **Helium Gas**

3.72

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

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

$$\Rightarrow \quad m = P\dot{V}\Delta t/RT = \frac{0.1 \times 0.5 \times 30 \times 60}{(0.46152 \times 323.15)} = \mathbf{0.603\ kg}$$

3.73

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

$$m_A = \frac{P_A V_A}{RT_A} = \frac{100 \times 1}{0.1886 \times 300} = 1.7674 \text{ kg}$$

$$m = \frac{P_B V_B}{RT_B} = \frac{250 \times 0.5}{0.1886 \times 400} = 1.6564 \text{ kg}$$

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

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

$$P_2 = \frac{m_2 R T_2}{V_2} = \frac{3.4243 \times 0.1886 \times 325}{1.5} = \mathbf{139.9\ kPa}$$

3.74

Verify the accuracy of the ideal gas model when it is used to calculate specific volume for saturated water vapor as shown in Fig. 3.9. Do the calculation for 10 kPa and 1 MPa.

Solution:

Look at the two states assuming ideal gas and then the steam tables.

Ideal gas:

$v = RT/P \;\Rightarrow\; v_1 = 0.46152 \times (45.81 + 273.15)/10 = 14.72 \text{ m}^3/\text{kg}$

$v_2 = 0.46152 \times (179.91 + 273.15)/1000 = 0.209 \text{ m}^3/\text{kg}$

Real gas:

Table B.1.2: $v_1 = \mathbf{14.647} \text{ m}^3/\text{kg}$ so error = 0.3 %

$v_2 = \mathbf{0.19444} \text{ m}^3/\text{kg}$ so error = 7.49 %

3.75

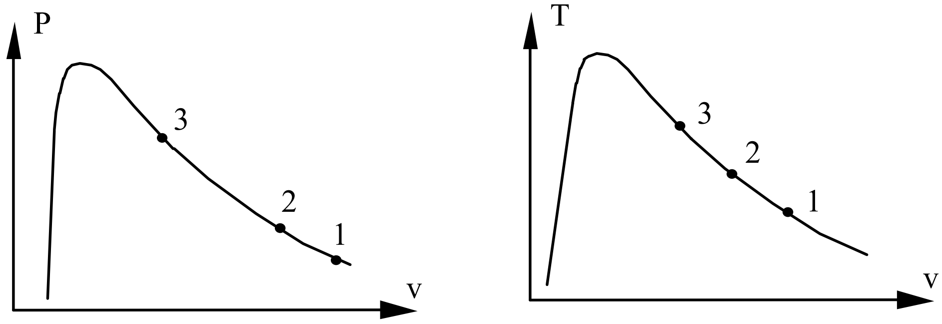
Assume we have 3 states of saturated vapor R-134a at +40 °C, 0 °C and -40 °C. Calculate the specific volume at the set of temperatures and corresponding saturated pressure assuming ideal gas behavior. Find the percent relative error = $100(v - v_g)/v_g$ with v_g from the saturated R-134a table.

Solution:

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

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

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



3.76

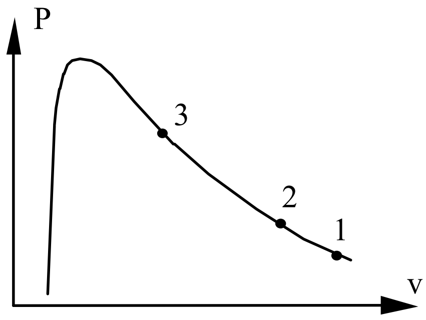
Do Problem 3.75, but for the substance R-12.

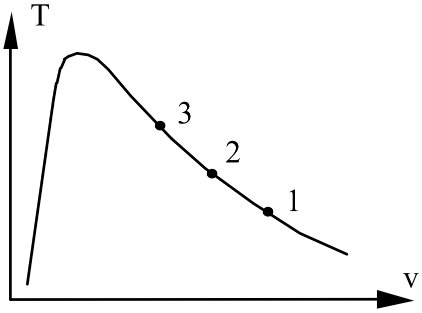
Solution:

R-12. Table values from Table B.3.1 P_{sat}, $v_g(T)$

Ideal gas constant from Table A.5: $R_{R\text{-}12} = 0.08149$ kJ/kg K

T	P_{sat} , kPa	v_g	$v_{ID.G.} = RT / P_{sat}$	error %
-40 °C	64.2	0.24191	0.2497	3.2
0 °C	308.6	0.05539	0.06086	9.9
40 °C	960.7	0.01817	0.02241	23.4





3.77

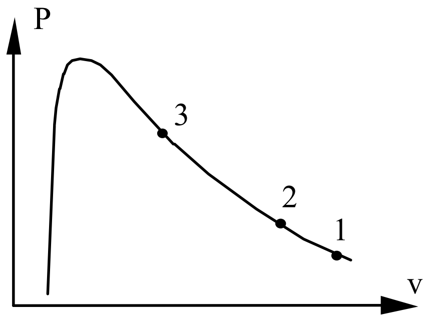
Do Problem 3.75, but for the substance ammonia.

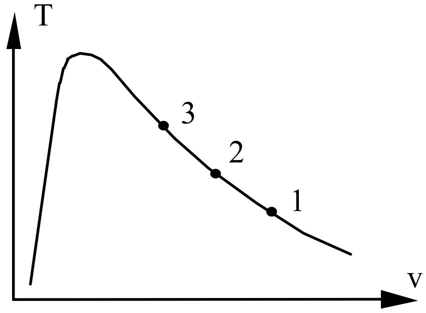
Solution:

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	$v_{ID.G.} = RT / P_{sat}$	error %
-40 °C	71.7	1.5526	1.5875	2.25
0 °C	429.6	0.28929	0.3104	7.3
40 °C	1555	0.08313	0.09832	18.3





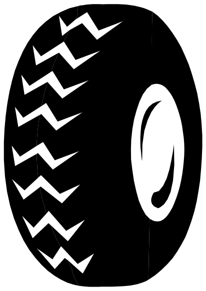
3.78

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 and that air is an ideal gas

$$P_2 = P_1 \times T_2/T_1$$
$$= 190 \times \frac{283.15}{263.15} = \mathbf{204.4\ kPa}$$



3.79

An initially deflated and flat balloon is connected by a valve to a 12 m^3 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

$$P = 400 = P_0 + C\,(\,1 - \frac{1}{4}\,)\,\frac{1}{4} = 100 + C \times 3/16 \qquad => \qquad C = 1600$$

The pressure is: $P = 100 + 1600\,(\,1 - X^{-1})\,X^{-1};\qquad X = D\,/\,D_1$

Differentiate to find max: $\frac{dP}{dD} = C\,(\,- X^{-2} + 2\,X^{-3}\,)\,/\,D_1 = 0$

$$=> \; - X^{-2} + 2\,X^{-3} = 0 \;=> \quad X = 2$$

at max P => $D = 2D_1 = 2$ m; $\qquad V = \frac{\pi}{6} D^3 = 4.18\ m^3$

$$\text{Pmax} = 100 + 1600\,(\,1 - \frac{1}{2}\,)\,\frac{1}{2} = \mathbf{500\ kPa}$$

Helium is ideal gas A.5: $m = \frac{PV}{RT} = \frac{500 \times 4.189}{2.0771 \times 293.15} = 3.44$ kg

$$m_{TANK,\,1} = \frac{PV}{RT} = \frac{2000 \times 12}{2.0771 \times 293.15} = 39.416\ \text{kg}$$

$m_{TANK,\,2} = 39.416 - 3.44 = 35.976$ kg

$P_{T2} = m_{TANK,\,2}\,RT/V = (\,m_{TANK,\,1}\,/\,\,m_{TANK,\,2}\,) \times P_1 = \mathbf{1825.5\ kPa}$

Compressibility Factor

3.80

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

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

$$m = \frac{PV}{ZRT} = \frac{3000 \times 5}{0.96 \times 0.2081 \times 243.2} = \mathbf{308.75\ kg}$$

Ideal gas $Z = 1$

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

3.81

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 $T = 40°C = 313.15\text{ K},\ T_c = 405.5\text{ K},\ P_c = 11.35\text{ MPa}$ from Table A.1

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

Ideal gas: $v = \frac{RT}{P} = \frac{0.48819 \times 313}{500} = \mathbf{0.3056\ m^3/kg} \quad \Rightarrow \ \mathbf{4.5\%\ error}$

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

$$v = \frac{ZRT}{P} = \mathbf{0.2964\ m^3/kg} \quad \Rightarrow \ \mathbf{1.4\%\ error}$$

3.82

A new refrigerant R-125 is stored as a liquid at -20 ^{o}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

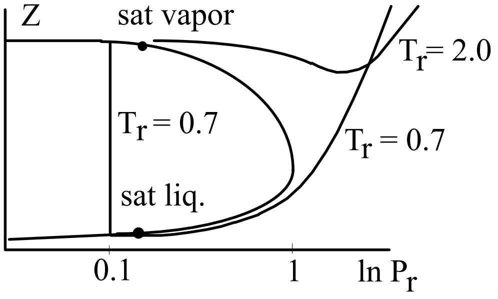
$$T_r = T / T_c = 253.15 / 339.2 = 0.746$$

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

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

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

$$PV_{liq} = Z_f m_{liq} RT = 0.029 \times 1.5 \times 0.06927 \times 253.15 / 579 = \mathbf{0.0013\ m^3}$$



3.83

Many substances that normally do not mix well do so easily under supercritical pressures. A mass of 125 kg ethylene at 7.5 MPa, 296.5 K is stored for such a process. How much volume does it occupy?

Solution:

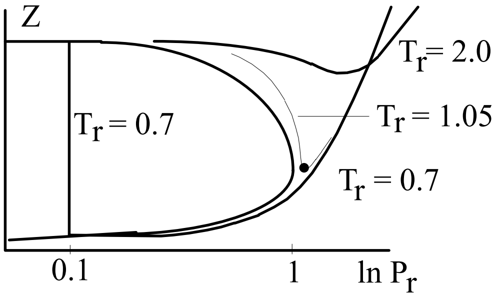
There is no section B table for ethylene so use compressibility chart.

Table A.2: Ethylene $T_c = 282.4$ K $P_c = 5.04$ MPa

$T_r = T/T_c = 296.5 / 282.4 = 1.05$; $P_r = P/P_c = 7.5 / 5.04 = 1.49$

$Z = 0.32$ from Figure D.1

$V = mZRT / P = 125 \times 0.32 \times 0.2964 \times 296.5 / 7500 = \mathbf{0.469\ m^3}$



3.84

Carbon dioxide at 330 K is pumped at a very high pressure, 10 MPa, into an oil-well. As it penetrates the rock/oil the oil viscosity is lowered so it flows out easily. For this process we need to know the density of the carbon dioxide being pumped.

Solution:

There is not a B section table so use compressibility chart

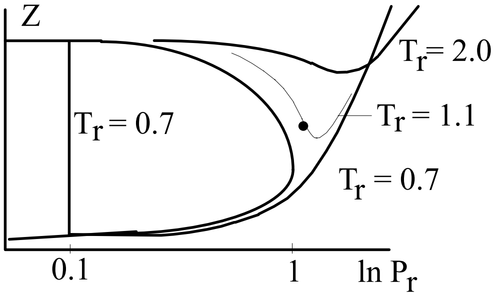
Table A.2 CO2: $T_c = 304.1$ K $P_c = 7.38$ MPa

$T_r = T/T_c = 330/304.1 = 1.085$

$P_r = P/P_c = 10/7.38 = 1.355$

From Figure D.1: $Z \approx 0.45$

$\rho = 1/v = P / ZRT = 10000/(0.45 \times 0.1889 \times 330) =$ **356 kg/m^3**



3.85

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 ^{o}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

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

$R = \bar{R}/M = 8.31451 / 152.93 = 0.0544$

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

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

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

$P = P_r \times P_c = 42.5$

$v_{fg} = Z_{fg}\ RT/P = 0.9768 \times 0.0544 \times 243 / 42.5 =$ **0.304 m^3/kg**

3.86

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:

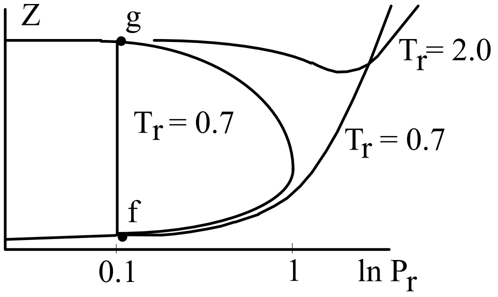
We need to find the property v the mass is: $m = V/v$

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: $Z_f \approx 0.02$; $Z_g \approx 0.9$; $P_{r\,sat} = 0.1$



$P = P_{sat} = P_{r\,sat} \times P_c = 0.1 \times 3.80 \times 1000 = 380$ kPa

$v_f = Z_f RT/P = 0.02 \times 0.14304 \times 300/380 = 0.00226\ m^3/kg$

$v_g = Z_g RT/P = 0.9 \times 0.14304 \times 300/380 = 0.1016\ m^3/kg$

$v = 0.00226 + 0.75 \times (0.1016 - 0.00226) = 0.076765\ m^3/kg$

$$m = \frac{V}{v} = \frac{0.1}{0.076765} = \mathbf{1.303\ kg}$$

3.87

Refrigerant R-32 is at -10 °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

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

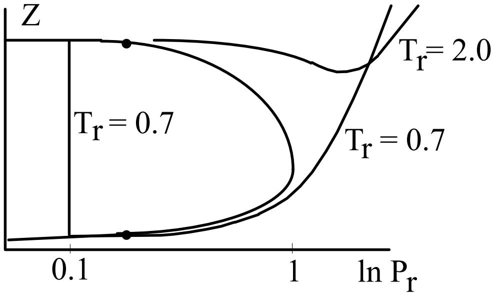
From Table D.4 or Figure D.1, $Z_f \approx 0.029$; $Z_g \approx 0.86$; $P_{r\,sat} \approx 0.16$

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

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

$= [0.029 + 0.15 \times (0.86 - 0.029)] \times 0.1598 \times 263 / 925$

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



3.88

A mass of 2 kg of acetylene is in a 0.045 m^3 rigid container at a pressure of 4.3 MPa. Use the generalized charts to estimate the temperature. (This becomes trial and error).

Solution:

Table A.2, A.5: $P_r = 4.3/6.14 = 0.70$; $T_c = 308.3$ K; $R = 0.3193$ kJ/kg K

$$v = V/m = 0.045/2 = 0.0225 \text{ m}^3\text{/kg}$$

State given by (P, v) $\quad v = \frac{ZRT}{P}$

Since Z is a function of the state Fig. D.1 and thus T, we have trial and error.

Try sat. vapor at $P_r = 0.7$ => Fig. D.1: $Z_g = 0.59$; $T_r = 0.94$

$$v_g = 0.59 \times 0.3193 \times 0.94 \times 308.3/4300 = 0.0127 \text{ m}^3\text{/kg} \quad \text{too small}$$

$$T_r = 1 \quad \Rightarrow \; Z = 0.7 \;\Rightarrow\; v = \frac{0.7 \times 0.3193 \times 1 \times 308.3}{4300} = 0.016 \text{ m}^3\text{/kg}$$

$$T_r = 1.2 \;\Rightarrow\; Z = 0.86 \;\Rightarrow\; v = \frac{0.86 \times 0.3193 \times 1.2 \times 308.3}{4300} = 0.0236 \text{ m}^3\text{/kg}$$

Interpolate to get: $T_r \approx 1.17$ $\quad$ **$T \approx 361$ K**

3.89

A substance is at 2 MPa, 17°C in a 0.25-m^3 rigid tank. Estimate the mass from the compressibility factor if the substance is a) air, b) butane or c) propane.

Solution:

Figure D.1 for compressibility Z and table A.2 for critical properties.

$P_r = P/P_c$ and $T_r = T/T_c$

Air is a mixture so we will estimate from the major component.

Nitrogen $P_r = 2/3.39 = 0.59$; $T_r = 290/126.2 = 2.3$; $Z \approx 0.98$

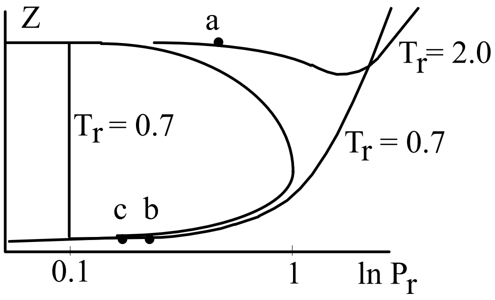
$m = PV/ZRT = 2000 \times 0.25/(0.98 \times 0.2968 \times 290) =$ **5.928 kg**

Butane $P_r = 2/3.80 = 0.526$; $T_r = 290/425.2 = 0.682$; $Z \approx 0.085$

$m = PV/ZRT = 2000 \times 0.25/(0.085 \times 0.14304 \times 290) =$ **141.8 kg**

Propane $P_r = 2/4.25 = 0.47$; $T_r = 290/369.8 = 0.784$; $Z \approx 0.08$

$m = PV/ZRT = 2000 \times 0.25/(0.08 \times 0.18855 \times 290) =$ **114.3 kg**



Review Problems

3.90

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 m^3/kg $v > v_g$ superheated vapor, **T = 120 °C**

2) 10 MPa, 0.01 m^3/kg => two-phase $v < v_g$

$x = (0.01 – 0.001452) / 0.01657 = \mathbf{0.516}$

b) Nitrogen, N_2, table B.6

1) 1 MPa, 0.03 m^3/kg => superheated vapor since $v > v_g$

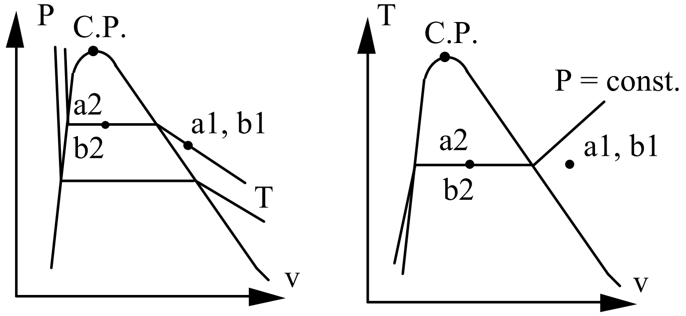
Interpolate between sat. vapor and superheated vapor B.6.2:

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

2) 100 K, 0.03 m^3/kg => sat. liquid + vapor as two-phase $v < v_g$

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

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



3.91

Fill out the following table for substance ammonia:

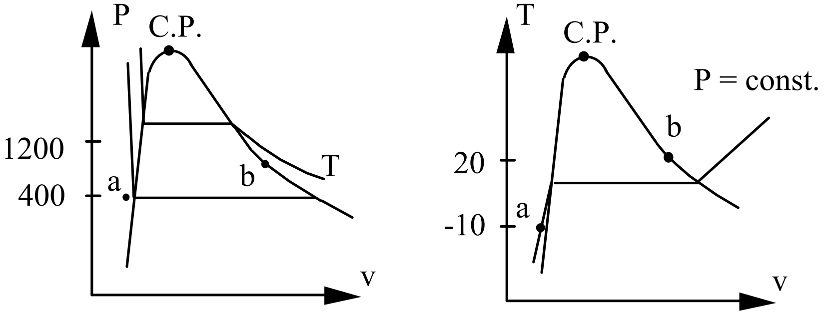
Solution:

	P [kPa]	T [^{o}C]	v [m^3/kg]	x
a)	400	-10	**0.001534**	**Undefined**
b)	**855**	**20**	0.15	1.0

a) B.2.1 $P > P_{sat}(-10^oC) = 291$ kPa => compressed liquid

$v \cong v_f = 0.001534\ m^3/kg$

b) B.2.1 search along the v_g values



3.92

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

Solution:

a. H_2O $T = 120°C$ $v = 0.5\ m^3/kg$

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 $v = 1.8\ m^3/kg$

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

sup. vap., interpolate in Table B.1.3

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

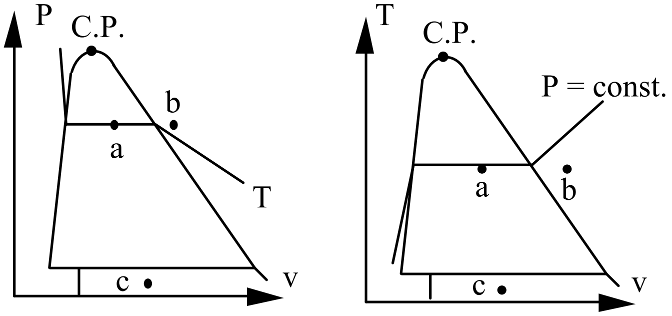
c. H_2O $T = 263$ K $v = 0.2\ m^3/kg$

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.



3.93

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

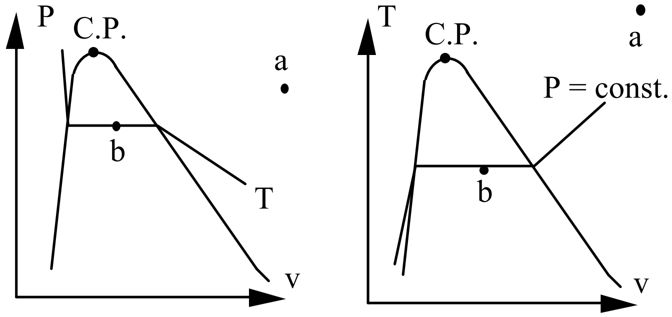
T = **71.4°C**

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**



3.94

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

Solution:

a. R-22 $T = 10°C$ $v = 0.01\ m^3/kg$

Table B.4.1 $v < v_g = 0.03471\ m^3/kg$

sat. liq. + vap. $P = P_{sat} = 680.7$ kPa,

$x = (v - v_f)/v_{fg} = (0.01 - 0.0008)/0.03391 = 0.2713$

b. H_2O $T = 350°C$ $v = 0.2\ m^3/kg$

Table B.1.1 at given T: $v > v_g = 0.00881$

sup. vap. $P \cong 1.40$ MPa, x = undefined

c. R-12 $T = -5\ °C$ $P = 200$ kPa

sup. vap. ($P < P_g$ at -5°C)

Table B 3.2:

$v = 0.08354\ m^3/kg$ at $-12.5°C$

$v = 0.08861\ m^3/kg$ at $0°C$

=> $v = 0.08658\ m^3/kg$ at $-5°C$

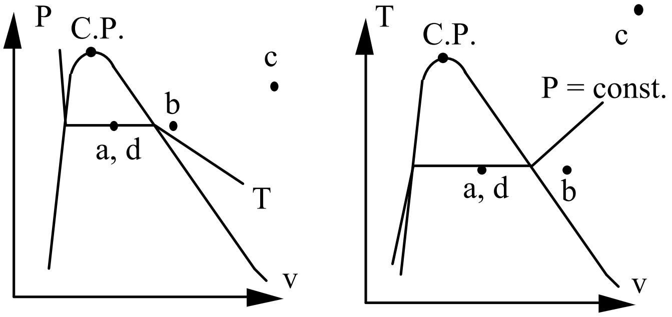
d. R-134a $P = 294$ kPa, $v = 0.05\ m^3/kg$

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

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.



3.95

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-22 at $T = 10°\text{C}$, $v = 0.036\ \text{m}^3/\text{kg}$: 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

$$P = 680.7 + (600 - 680.7)\frac{0.036-0.03471}{0.04018-0.03471} = \mathbf{661.7\ kPa}$$

b) H_2O $v = 0.2\ \text{m}^3/\text{kg}$, $x = 0.5$: Table B.1.1

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

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

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

An interpolation gives $T \cong \mathbf{149.4°C}$, $P \cong \mathbf{468.2\ kPa}$

c) H_2O $T = 60°\text{C}$, $v = 0.001016\ \text{m}^3/\text{kg}$: Table B.1.1 $v < v_f = 0.001017$

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

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

d) NH_3 $T = 30°\text{C}$, $P = 60$ kPa : Table B.2.1 $P < P_{sat}$

=> **sup. vapor** interpolate in Table B.2.2

$$v = 2.94578 + (1.95906 - 2.94578)\frac{60 - 50}{75 - 50} = \mathbf{2.551\ m^3/kg}$$

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

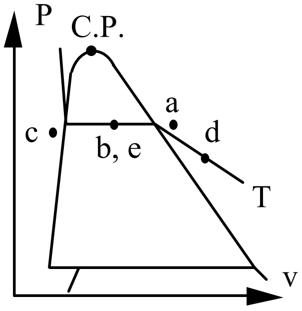
e) R-134a $v = 0.005\ \text{m}^3/\text{kg}$, $x = 0.5$: **sat. liq. + vap.** Table B.5.1

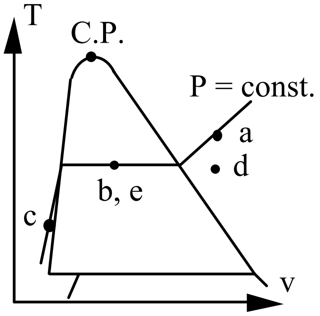
$v = (1-x)\ v_f + x\ v_g \Rightarrow v_f + v_g = 0.01\ \text{m}^3/\text{kg}$

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

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

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





3.96

A 5 m long vertical tube of cross sectional area 200 cm^2 is placed in a water fountain. It is filled with 15^{o}C water, the bottom closed and the top open to the 100 kPa atmosphere.

a) How much water is in the tube?

b) What is the pressure at the bottom of the tube

Solution:

State 1: slightly compressed liquid from Table B.1.1

Mass: $m = \rho\ V = V/v = AH/v = 200 \times 10^{-4} \times 5/0.001001 = \mathbf{99.9\ kg}$

$$\Delta P = \rho\ gH = gH/v = 9.80665 \times 5/0.001001$$

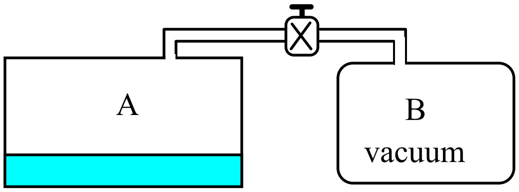
$$= 48\ 984\ \text{Pa} = 48.98\ \text{kPa}$$

$$P_{tot} = P_{top} + \Delta P = \mathbf{149\ kPa}$$

3.97

Consider two tanks, A and B, connected by a valve, as shown in Fig. P3.97. Each has a volume of 200 L and tank A has R-12 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.3.1 $v_f = 0.000763\ \mathrm{m^3/kg}$, $v_g = 0.026854\ \mathrm{m^3/kg}$

$$m_{A1} = \frac{V_{liq1}}{v_{f\,25°C}} + \frac{V_{vap1}}{v_{g\,25°C}} = \frac{0.1 \times 0.2}{0.000763} + \frac{0.9 \times 0.2}{0.026854}$$

$$= 26.212 + 6.703 = 32.915\ \mathrm{kg}$$

$$x_{A1} = \frac{6.703}{32.915} = 0.2036\ ;$$

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

$$m_{B2} = \frac{V_B}{v_{g\,25°C}} = \frac{0.2}{0.26854} = 7.448\ \mathrm{kg}$$

State A2: mass left is $m_{A2} = 32.915 - 7.448 = 25.467\ \mathrm{kg}$

$$v_{A2} = \frac{0.2}{25.467} = 0.007853 = 0.000763 + x_{A2} \times 0.026091$$

$x_{A2} = 0.2718$ $\Delta x =$ **6.82%**

3.98

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.

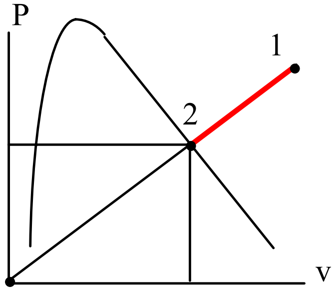
Solution:

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

Process: m is constant and $P = C_0V = C_0m\, v = C\, v$

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

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 $v_g = 0.09963 \Rightarrow C = 20074$ (low)

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

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

Interpolate to get the right C $\Rightarrow$ $\mathbf{P_2 = 2270}$ **kPa**

3.99

A 1 m^3 rigid tank has air at 1500 kPa and ambient 300 K connected by a valve to a piston cylinder. The piston of area 0.1 m^2 requires 250 kPa below it to float. The valve is opened and the piston moves slowly 2 m up and the valve is closed. During the process air temperature remains at 300 K. What is the final pressure in the tank?

$$m_A = \frac{P_A V_A}{RT_A} = \frac{1500\times1}{0.287\times300} = 17.422 \text{ kg}$$

$$m_{B2} - m_{B1} = \frac{\Delta V_A}{v_B} = \frac{\Delta V_B P_B}{RT} = \frac{0.1\times2\times250}{0.287\times300} = 0.581 \text{ kg}$$

$$m_{A2} = m_A - (m_{B2} - m_{B1}) = 17.422 - 0.581 = 16.841 \text{ kg}$$

$$P_{A2} = \frac{m_{A2}RT}{V_A} = \frac{16.841\times0.287\times300}{1} = \mathbf{1450\ kPa}$$

3.100

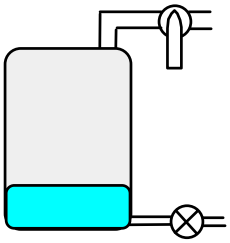
A tank contains 2 kg of nitrogen at 100 K with a quality of 50%. Through a volume flowmeter and valve, 0.5 kg is now removed while the temperature remains constant. Find the final state inside the tank and the volume of nitrogen removed if the valve/meter is located at

a. The top of the tank

b. The bottom of the tank

Solution

Table B.6.1:



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

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

$m_2 = m_1 - 0.5 = 1.5 \text{ kg}$

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

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

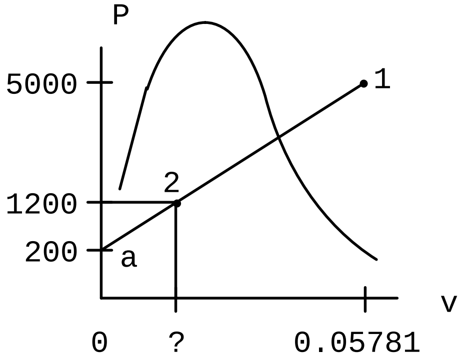
Top: flow out is sat. vap. $v_g = 0.031216 \text{ m}^3/\text{kg}$, $V_{out} = m_{out} v_g = \mathbf{0.0156 \ m^3}$

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

3.101

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:



1: Table B.1.3 ⇒ $v_1 = 0.05781 \text{ m}^3/\text{kg}$

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

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

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

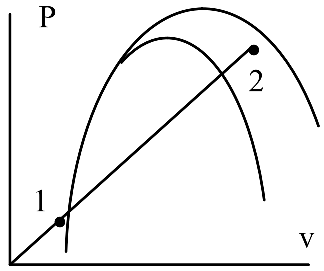
$v_2 < v_g$(1200 kPa) so two-phase T_2 = **188°C**

⇒ $x_2 = (v_2 - 0.001139)/0.1622 = 0.0672$

3.102

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

$v_g(T_2) = 0.12736$; $P_g(T_2) = 1.5538$ MPa

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

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

P_2 = 1553.8 kPa, $x_2 = (0.0161 - 0.001156) / 0.1262 =$ **0.118**

3.103

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:

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

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

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

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

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

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

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

3.104

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: $v_1 = 0.0016 + 0.9(0.205525 - 0.0016) = 0.18513\ m^3/kg$

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

$m_1 = V/v = 0.005/0.18513 = 0.027\ kg$

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:

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

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

At P_2, v_2: $\quad T_2 =$ **70.9°C**

3.105

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. P3.105. 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?

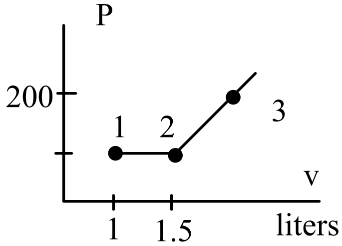
Solution:

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

$m = V_1 / v_1 = \frac{0.001}{1.20661} = 8.288\times10^{-4}$ 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)

$200 = 120.8 + (100/0.01767^{\,2}) \times 8.288\times10^{-4}(v_3 - 1.8099)$

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

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

3.106

Refrigerant-12 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.

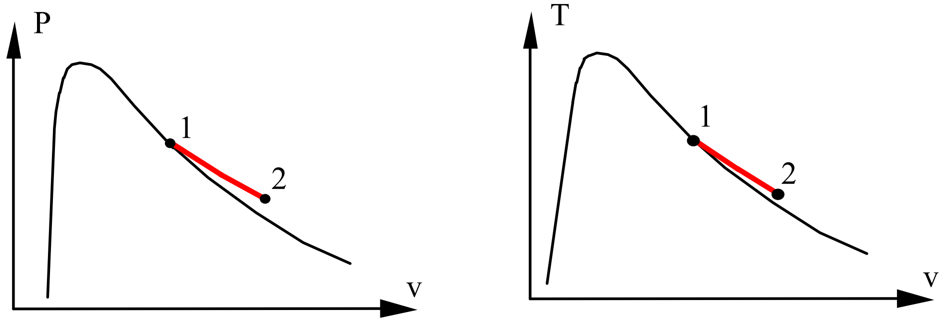
Solution:

State 1: 50°C, x = 1 Table B.3.1: $P_1 = 1219.3$ kPa, $v_1 = 0.01417\ m^3/kg$

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

State 2: 100 kPa and $v_2 = v_1P_1/P_2 =$ **$0.1728\ m^3/kg$**

$T_2 \cong$ **-13.2°C** from Table B.3.2 Notice T **not** constant



3.107

A 1-m^3 rigid tank with air at 1 MPa, 400 K is connected to an air line as shown in Fig. P3.107. 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.

$$m_{air1} = \frac{P_1 V}{RT_1} = \frac{1000 \times 1}{0.287 \times 400} = \mathbf{8.711\ kg}$$

$$m_{air2} = \frac{P_2 V}{RT_2} = \frac{5000 \times 1}{0.287 \times 450} = \mathbf{38.715\ kg}$$

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

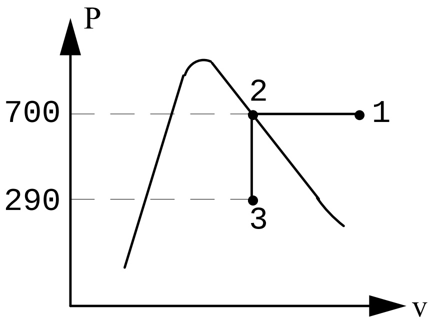
$$P_3 = P_2 \times (T_3/T_2) = 5000 \times (300/450) = \mathbf{3.33\ MPa}$$

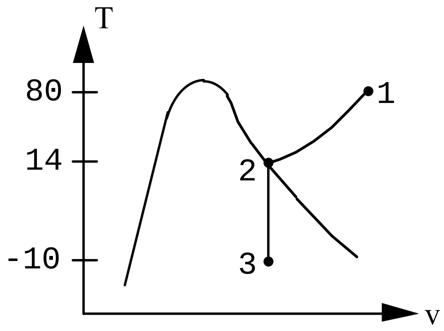
3.108

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





3.109

A cylinder has a thick piston initially held by a pin as shown in Fig. P3.109. 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 $m_p = A_p \times l \times \rho$ $\qquad\qquad \rho_{piston} = 8000$ 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 $V_2 = V_1 \times H_2/H_1 = V_1 \times 150 / 100$

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**

3.110

For a certain experiment, R-22 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-22 fixed volume (V) & mass (m) at 20°C

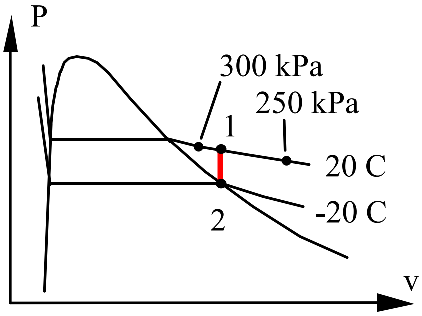
Process: cool to -20°C at constant v, so we assume saturated vapor

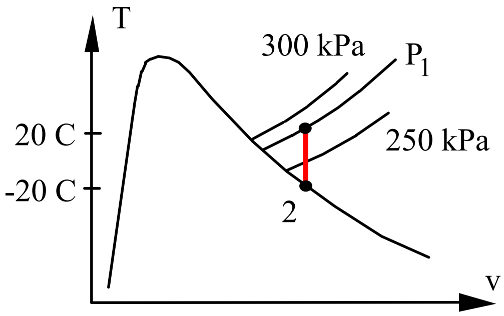
State 2: $v_2 = v_{g\text{ at -20°C}} = 0.092843\ \mathrm{m^3/kg}$

State 1: 20°C, $v_1 = v_2 = 0.092843\ \mathrm{m^3/kg}$

interpolate between 250 and 300 kPa in Table B.4.2

=> $\mathbf{P_1 = 291\ kPa}$





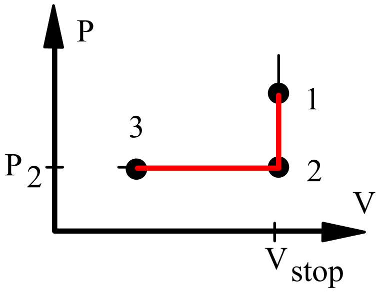
3.111

A piston/cylinder arrangement, shown in Fig. P3.111, 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 $A_p = \frac{\pi}{4} \times 0.1^2 = 0.00785 \text{ m}^2$

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:

$$T_2 = T_1 \times \frac{P_2}{P_1} = 573.15 \times \frac{162.5}{250} = \mathbf{372.5\ K}$$

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 $P_2 = P_3$ => $V_3 = V_2 \times \frac{T_3}{T_2} = 1.96 \times \frac{293.15}{372.5} = \mathbf{1.54\ L}$

$\Delta H = (V_2 - V_3)/A = (1.96-1.54) \times 0.001/0.00785 =$ **0.053 m = 5.3 cm**

3.112

Air in a tank is at 1 MPa and room temperature of 20°C. It is used to fill an initially empty balloon to a pressure of 200 kPa, at which point the radius is 2 m and the temperature is 20°C. Assume the pressure in the balloon is linearly proportional to its radius and that the air in the tank also remains at 20°C throughout the process. Find the mass of air in the balloon and the minimum required volume of the tank.

Solution: Assume air is an ideal gas.

Balloon final state: $V_2 = (4/3)\,\pi\, r^3 = (4/3)\,\pi\, 2^3 = 33.51\ \text{m}^3$

$$m_{2bal} = \frac{P_2V_2}{RT_2} = \frac{200 \times 33.51}{0.287 \times 293.15} = \mathbf{79.66\ kg}$$

Tank must have $P_2 \geq 200$ kPa => $m_{2\,tank} \geq P_2\, V_{TANK} / RT_2$

Initial mass must be enough: $m_1 = m_{2bal} + m_{2\,tank} = P_1V_1 / R\, T_1$

$$P_1V_{TANK} / R\, T_1 = m_{2bal} + P_2V_{TANK} / RT_2 \quad =>$$

$$V_{TANK} = \frac{RTm_{2bal}}{P_1 - P_2} = \frac{0.287 \times 293.15 \times 79.66}{1000 - 200} = \mathbf{8.377\ m^3}$$

3.113

A cylinder is fitted with a 10-cm-diameter piston that is restrained by a linear spring (force proportional to distance) as shown in Fig. P3.113. The spring force constant is 80 kN/m and the piston initially rests on the stops, with a cylinder volume of 1 L. The valve to the air line is opened and the piston begins to rise when the cylinder pressure is 150 kPa. When the valve is closed, the cylinder volume is 1.5 L and the temperature is 80°C. What mass of air is inside the cylinder?

Solution:

$F_s = k_s \Delta x = k_s \, \Delta V/A_p$; $V_1 = 1 \text{ L} = 0.001 \text{ m}^3$, $A_p = \frac{\pi}{4} 0.1^2 = 0.007854 \text{ m}^2$

State 2: $V_3 = 1.5 \text{ L} = 0.0015 \text{ m}^3$; $T_3 = 80°\text{C} = 353.15 \text{ K}$

The pressure varies linearly with volume seen from a force balance as:

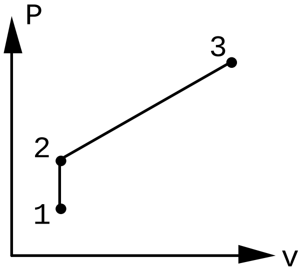
$$PA_p = P_0 \, A_p + m_p \, g + k_s(V - V_0)/A_p$$

Between the states 1 and 2 only volume varies so:

$$P_3 = P_2 + \frac{k_s(V_3\text{-}V_2)}{A_p^{\,2}} = 150 + \frac{80\times10^3(0.0015 - 0.001)}{0.007854^2 \times 1000}$$

$$= 798.5 \text{ kPa}$$

$$m = \frac{P_3V_3}{RT_3} = \frac{798.5 \times 0.0015}{0.287 \times 353.15} = \mathbf{0.012\ kg}$$



3.114

A 500-L tank stores 100 kg of nitrogen gas at 150 K. To design the tank the pressure must be estimated and three different methods are suggested. Which is the most accurate, and how different in percent are the other two?

a. Nitrogen tables, Table B.6

b. Ideal gas

c. Generalized compressibility chart, Fig. D.1

Solution:

State 1: 150 K, $v = V/m = 0.5/100 = 0.005\ \text{m}^3/\text{kg}$

a) Table B.6, interpolate between 3 & 6 MPa with both at 150 K:

3 MPa : $v = 0.01194\ \text{m}^3/\text{kg}$, 6 MPa : $v = 0.0042485\ \text{m}^3/\text{kg}$

$P = 3 + (0.005-0.01194)\times(6-3)/(0.0042485-0.01194) = 5.707$ MPa

b) Ideal gas table A.5: $P = \frac{RT}{v} = \frac{0.2968 \times 150}{0.005} = 8.904$ MPa

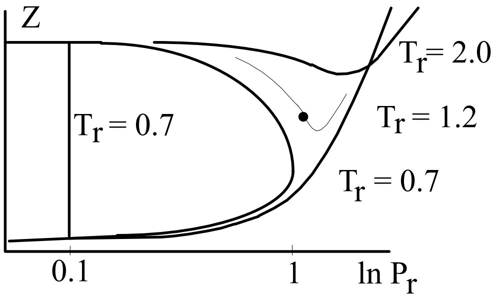
c) Table A.2 $T_c = 126.2$ K, $P_c = 3.39$ MPa so $T_r = 150/126.2 = 1.189$

Z is a function of P so it becomes trial and error. Start with P = 5.7 MPa

$$P_r \cong 1.68 \;\Rightarrow\; Z = 0.60 \;\Rightarrow\; P = \frac{ZRT}{v} = 5342 \text{ kPa}$$

Now repeat finding the proper Z value.

$$\Rightarrow\; P_r = 1.58 \;\Rightarrow\; Z = 0.62 \;\Rightarrow\; P = 5520 \text{ kPa OK}$$



ANSWER: **a) is the most accurate** with others off by b) **60%** c) **1%**

3.115

What is the percent error in pressure if the ideal gas model is used to represent the behavior of superheated vapor R-22 at 50°C, 0.03082 m^3/kg? What if the generalized compressibility chart, Fig. D.1, is used instead (iterations needed)?

Solution:

Real gas behavior: $P = 900$ kPa from Table B.4.2

Ideal gas constant: $R = \bar{R}/M = 8.31451/86.47 = 0.096155$ kJ/kg K

$P = RT/v = 0.096155 \times (273.15 + 50) / 0.03082$

$= \mathbf{1008\ kPa}$ **which is 12% too high**

Generalized chart Fig D.1 and critical properties from A.2:

$T_r = 323.2/363.3 = 0.875; \quad P_c = 4970$ kPa

Assume $P = 900$ kPa $\Rightarrow$ $P_r = 0.181$ $\Rightarrow$ $Z \cong 0.905$

$v = ZRT/P = 0.905 \times 0.096155 \times 323.15 / 900 = 0.03125$ too high

Assume $P = 950$ kPa $\Rightarrow$ $P_r = 0.191$ $\Rightarrow$ $Z \cong 0.9$

$v = ZRT/P = 0.9 \times 0.096155 \times 323.15 / 950 = 0.029473$ too low

$$P \cong 900 + (950 - 900) \times \frac{0.03082 - 0.029437}{0.03125 - 0.029437} = \mathbf{938\ kPa} \qquad \mathbf{4.2\ \%\ high}$$

Linear Interpolation

3.116

Find the pressure and temperature for saturated vapor R-12 with v = 0.1 m^3/kg

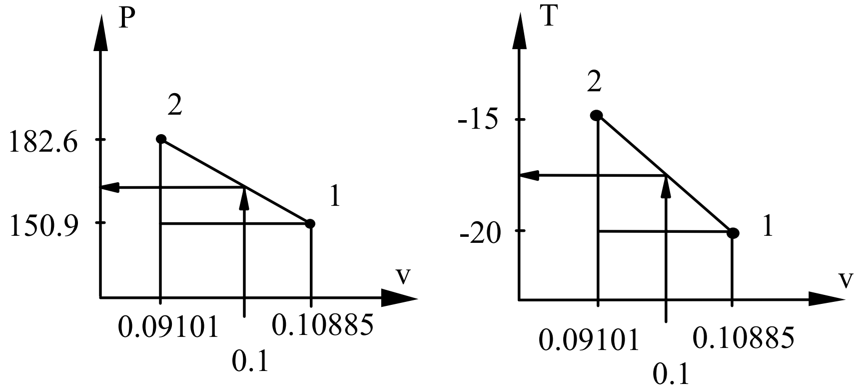
Solution:

Table B.3.1 Look at the saturated vapor column v_g and it is found between −20°C and −15°C. We must then do a linear interpolation between these values.

$$T = -20 + [\,-15 - (-20)]\,\frac{0.1 - 0.10885}{0.09101 - 0.10885}$$

$$= -20 + 5 \times 0.4961 = \mathbf{-17.5^{\circ}C}$$

$$P = 150.9 + (182.6 - 150.9) \times 0.4961 = \mathbf{166.6\ kPa}$$



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 (0.10885 - 0.1) to the side of the large triangle (0.10885 - 0.09101) is equal to 0.4961. This fraction of the total ΔP = 182.6 - 150.9 or ΔT = -15 -(-20) is added to the lower value to get the desired interpolated result.

3.117

Use a linear interpolation to estimate properties of ammonia to fill out the table below

	P [kPa]	T [°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.

$$T = 5 + (10 - 5)\,\frac{550 - 515.9}{615.2 - 515.9} = 5 + 5 \times 0.341 = \mathbf{6.7\ ^\circ C}$$

$$v_f = 0.001583 + (0.0016 - 0.001583)\ 0.341 = 0.001589 \text{ m}^3\text{/kg}$$

$$v_g = 0.24299 + (0.20541 - 0.24299)\ 0.341 = 0.230175 \text{ m}^3\text{/kg}$$

$$v = v_f + xv_{fg} = 0.001589 + 0.75(0.230175 - 0.001589)$$

$$= \mathbf{0.1729\ m^3/kg}$$

b) Interpolate between 50 and 100 kPa to get properties at 80 kPa

$$v = 2.8466 + (1.4153 - 2.8466)\,\frac{80 - 50}{100 - 50}$$

$$= 2.8466 + (-1.4313) \times 0.6 = \mathbf{1.9878\ m^3/kg}$$

x: Undefined

c) Table B.2.1: $v > v_g$ so the it is superheated vapor.

Table B.2.2 locate state between 300 and 400 kPa.

$$P = 300 + (400 - 300)\,\frac{0.4 - 0.44251}{0.32701 - 0.44251}$$

$$= 300 + 100 \times 0.368 = \mathbf{336.8\ kPa}$$

x: Undefined

3.118

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?

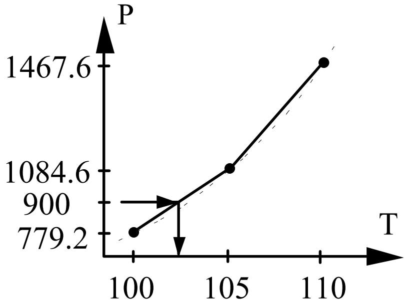
Solution:

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.



3.119

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 at 13°C,

$$P = 83.8 + (3/10) \times (86.2 - 83.8) = \mathbf{84.5\ kPa}$$

This could also be interpolated as following:

At 13°C, 50 kPa, $v = 0.45608 + (3/10) \times 0.0168 = 0.4611\ m^3/kg$

At 13°C, 100 kPa, $v = 0.22527 + (3/10) \times 0.0087 = 0.2279\ m^3/kg$

Interpolating at $0.3\ m^3/kg$.

$$P = 50 + (100 - 50) \times \frac{0.1611}{0.2332} = \mathbf{84.5\ kPa}$$

3.120

Find the specific volume of ammonia at 140 kPa and 0°C.

Solution:

The state is superheated vapor in Table B.2.2 between 100 and 150 kPa.

$$v = 1.3136 + (0.8689 - 1.3136)\,\frac{140 - 100}{150 - 100}$$

$$= 1.3136 + (-0.4447) \times 0.8 = \mathbf{0.9578\ m^3/kg}$$

3.121

Find the pressure of water at 200°C and specific volume of 1.5 m^3/kg.

Solution:

Table B.1.1: $v > v_g$ so that it is superheated vapor.

Table B.1.3: Between 100 kPa and 200 kPa

$$P = 100 + (200 - 100)\,\frac{1.5 - 2.17226}{1.08034 - 2.17226} = \mathbf{161.6\ kPa}$$

Computer Tables

3.122

Use the computer software to find the properties for water at the 4 states in Problem 3.33

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
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

3.123

Use the computer software to find the properties for ammonia at the 2 states listed in Problem 3.37

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
c)	1 (T, P)	Compressed liquid, x = undefined, $v = 0.001534$ m^3/kg
d)	No (v, x) entry so use 4 (T, x) OR 8 (P, x) several times	$T = 19.84^{\circ}$C, $P = 853.1$ kPa $T = 19.83^{\circ}$C, $P = 852.9$ kPa

3.124

Use the computer software to find the properties for ammonia at the 3 states listed in Problem 3.117

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

3.125

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.

$$T = 100 + (105 - 100)\,\frac{900 - 779.2}{1084.6 - 779.2}$$

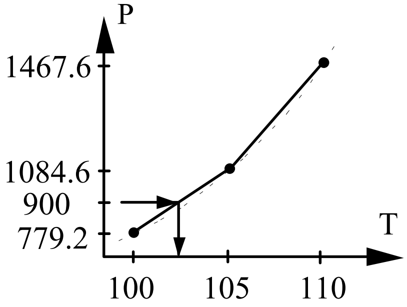
$$= 100 + 5 \times 0.3955 = 101.98\ \text{K}$$

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) $T = -171^\circ\text{C} = 102.15\ \text{K}$

So we notice that the curvature has only a minor effect.

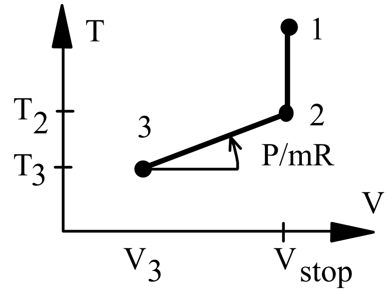


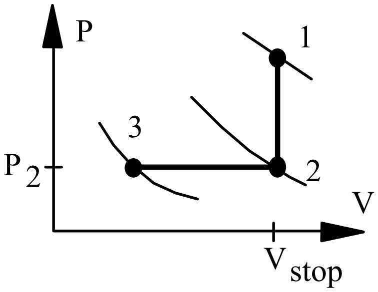
3.126

Write a computer program that lists the states P, T, and v along the process curve in Problem 3.111

State 1: 250 kPa, $300^{\circ}C = 573$ K
State 2: 162.5 kPa, 372.5 K
State 3: 162.5 kPa, 293 K

Since we have an ideal gas the relations among the pressure, temperature and the volume are very simple. The process curves are shown in the figure below.





3.127

Use the computer software to sketch the variation of pressure with temperature in Problem 3.41. 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.