Fundamentals of Thermodynamics 10th edition Borgnakke Solutions Manual

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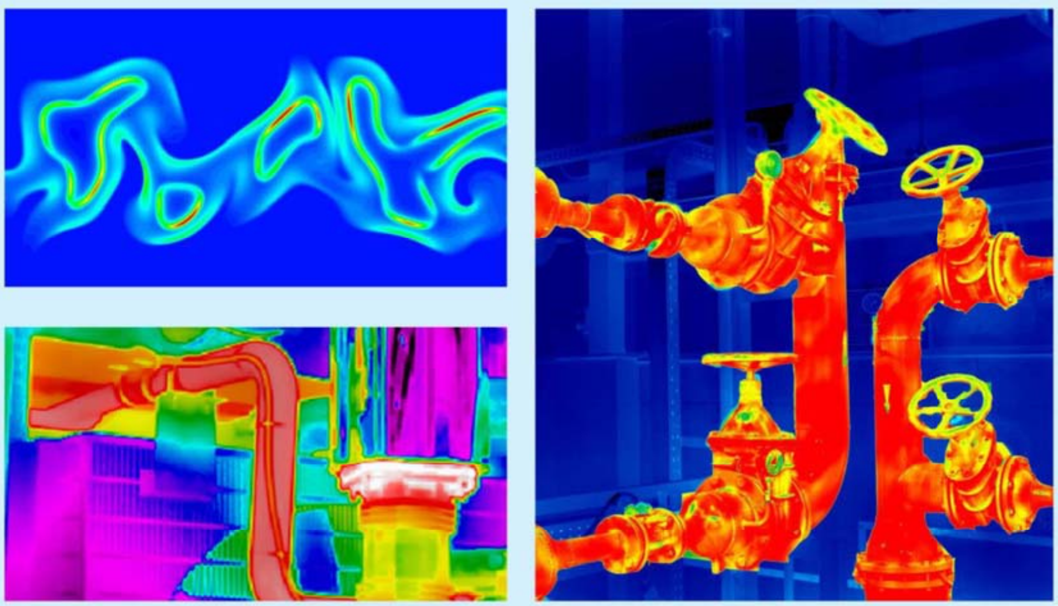
SOLUTION MANUAL
RESERVES CHAPTER 2

Tenth Edition

Fundamentals of Thermodynamics

Borgnakke · Sonntag



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August 2018

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In-Text Concept Questions

none

Concept Problems

R2.1

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

See Table B.2.2 it is a superheated vapor (gas).

$n = 0$ ($v = 1.4153$ m^3/kg)

Phase Diagrams, Triple and Critical Points

R2.2

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

Solution:

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

Mercury: T_a = -39°C = **234 K**

Zinc: T_b = 419°C = **692 K**

Silver: T_c = 961°C = **1234 K**

R2.3

Give the phase for the following states.

Solution:

a. CO_2 $T = 40°C$ $P = 0.5$ MPa Table A.2

$T > T_c$ => also $P << P_c$

superheated vapor assume ideal gas Table A.5

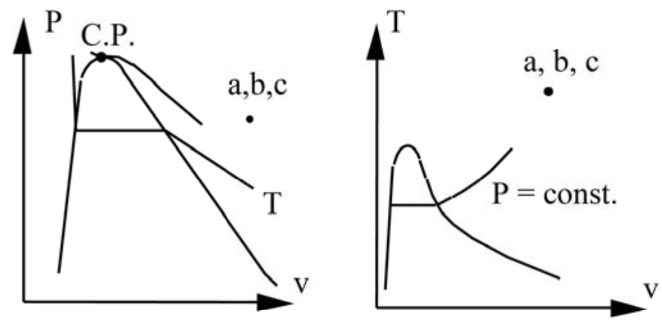
b. Air $T = 20°C$ $P = 200$ kPa Table A.2

$T > T_c$ => also $P << P_c$ for both components O_2 and N_2

superheated vapor assume ideal gas Table A.5

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

$T > T_c$ => also $P << P_c$ **superheated vapor**



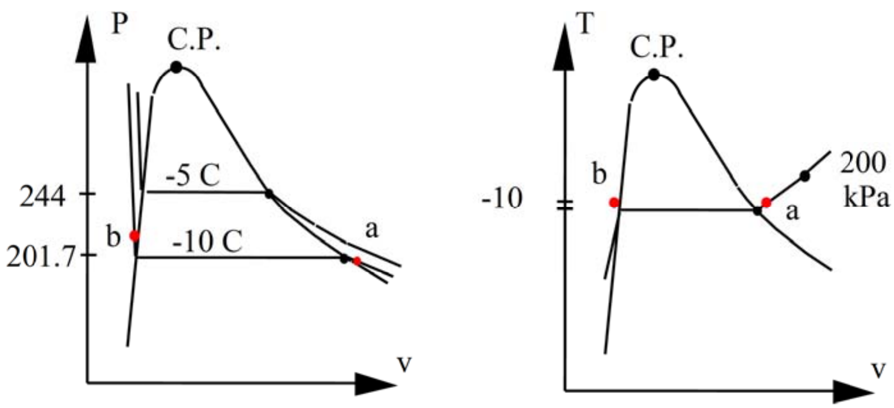
General Tables

R2.4

Cold R-134a is at 200 kPa, -10C what is the specific volume? Repeat for a pressure of 210 kPa same T. Indicate the two states in a P-v diagram (sketch).

a) See Table B.5.2 it is a superheated vapor (gas), $v = 0.10013 \text{ m}^3/\text{kg}$

b) Table B.5.1: at -10C P-sat is 201.7 kPa so if P is higher it is a liquid. No compressed liquid Table so use $v = v_f = 0.000755 \text{ m}^3/\text{kg}$



R2.5

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

a.	$P = 10$ MPa, $v = 0.003$ m^3/kg	b.	1 MPa, 190°C
c.	200°C, 0.1 m^3/kg	d.	10 kPa, 10°C

Solution:

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

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

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

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

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

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

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

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

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

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

$\Rightarrow \quad x = (v - v_f)/v_{fg} = (0.1 – 0.001156)/0.1262 = 0.7832$

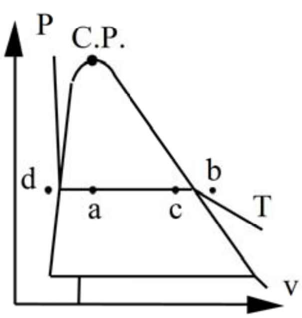
d. 10 kPa, 10°C : Only one of the two look-ups is needed

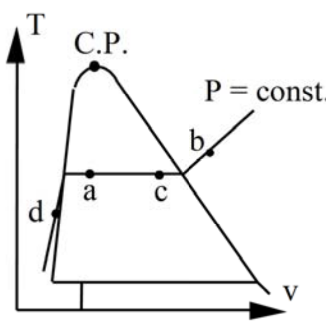
From B.1.1: $P > P_g = 1.2276$ kPa so compressed liquid

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

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

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





R2.6

For water at 400 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: $v_f = 0.001\,084\ m^3/kg$, $v_g = 0.46246\ m^3/kg$

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

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

The volumes are

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

So the volume fraction of vapor is

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

$$= \frac{0.1 \times 0.46246}{0.1 \times 0.46246 + 0.9 \times 0.001084} = \frac{0.046246}{0.0895279} = \mathbf{0.979}$$

Notice that the liquid volume is only about 2% of the total. We could also have found the overall $v = v_f + x v_{fg}$ and then $V = m\, v$.

R2.7

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

a)	R-410A	1) 0°C, 600 kPa	2) 0°C, 800 kPa
b)	Water	1) 160°C, 2000 kPa	2) 250°C, 2000 kPa

Solution:

a) From Table B.4.1 $\quad P_{sat}(0^\circ C) = 798.7$ kPa

1) 600 kPa < P_{sat} then it is superheated vapor, $v = 0.04595 \text{ m}^3/\text{kg}$

OR from Table B.1.2 $\quad T_{sat}(600 \text{ kPa}) = -8.67^\circ C$

$0^\circ C > T_{sat}$ then it superheated vapor

2) 800 kPa > P_{sat} then it is compressed liquid, no such table

TBL B.4.1 $\quad v = v_f = 0.000885 \text{ m}^3/\text{kg}$

b) Water H_2O :

1) Table B.1.1: $P > P_{sat}(160\ ^\circ C) = 617.8$ kPa Compressed liquid

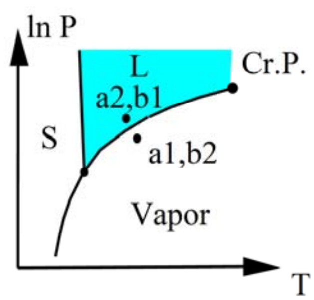
B.1.4: 2000 kPa $\quad v = 0.001101 \text{ m}^3/\text{kg}$

2) Table B.1.1: $P < P_{sat}(250^\circ C) = 3973$ kPa Superheated vapor

Table B.1.2: $T > T_{sat}(2000 \text{ kPa}) = 212.42$ C sup. vapor

B.1.3 2000 kPa $\quad v = 0.11144 \text{ m}^3/\text{kg}$

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



R2.8

Give the missing property of P, T, v and x for R-134a at

a. $T = -20^{o}C$, $P = 200$ kPa

b. $P = 300$ kPa, $v = 0.071\ m^3/kg$

Solution:

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

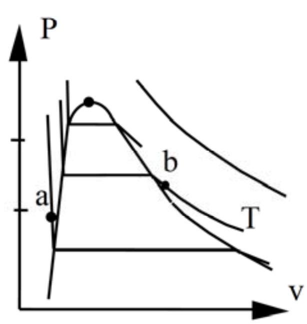
$v \sim v_f = 0.000738\ m^3/kg$

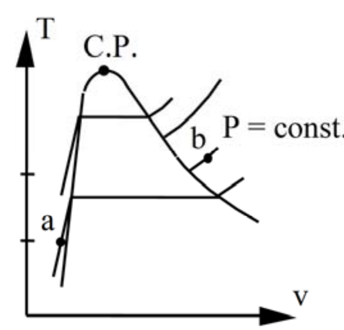
x = undefined

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

$T \approx 10°C$

x = undefined





R2.9

Give the missing property of P, T, v and x for these states.

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 $P > P_{sat} = 133.7$ 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

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

x = undefined

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

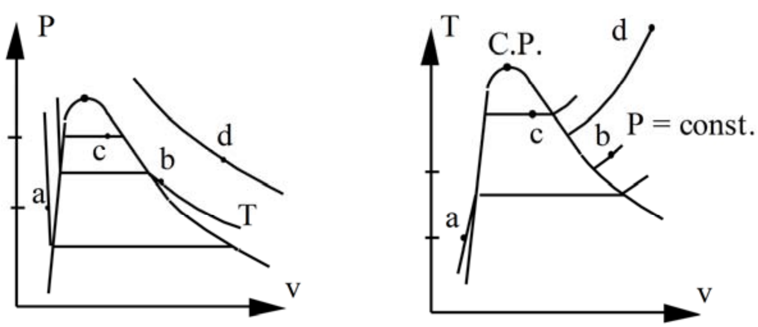
$$x = \frac{v - v_f}{v_{fg}} = \frac{0.04 - 0.002877}{0.04605} = 0.806$$

$P = P_{sat} = 1295.6$ kPa

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

located between 600 & 800 kPa

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



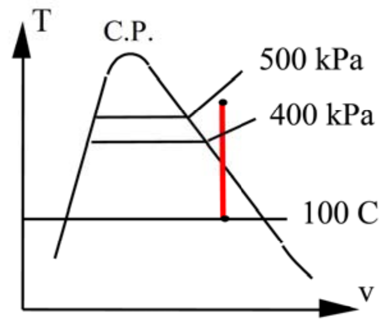
R2.10

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: $v = V/m = \text{constant}$

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

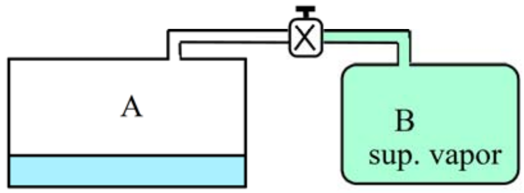


State 2: 200°C, 0.5 m^3/kg
Table B.1.3 between 400 and 500 kPa so interpolate

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

R2.11

Two tanks are connected as shown in the figure, 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) $\quad m_A = V_A/v_A = 1/0.5 = 2$ kg

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

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

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

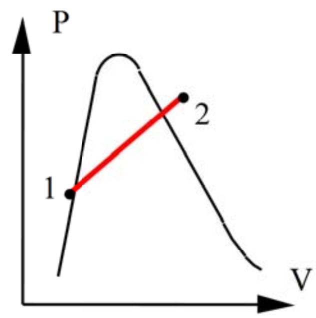
$$V_{tot} = V_A + V_B = 3.1606\ m^3$$

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

R2.12

Water in a piston/cylinder is at 90°C, 100 kPa, and the piston loading is such that pressure is linear in volume, $P = A + BV$. Heat is now added until it reaches a state of 200°C, 1400 kPa. Find the final specific volume and sketch the process in a P-v diagram.

Solution:



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

Check state 2 in Table B.1.1

$P_2 < P_{sat}$ so superheated vapor

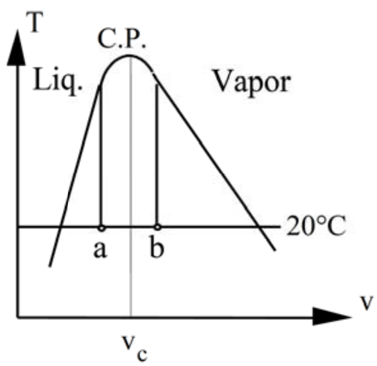
B.1.3: $v = 0.14302 \text{ m}^3/\text{kg}$

R2.13

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.

$\Rightarrow$ **level rises to top**

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

then it will reach saturated vapor.

$\Rightarrow$ **level falls**

R2.14

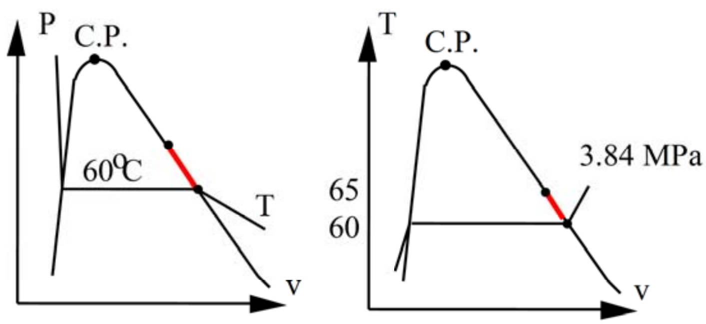
Saturated vapor R-410A at 60°C has its pressure increased to decrease the volume by 20% while the state is still saturated vapor. Find the new temperature and pressure.

State 1: B.4.1 $v_1 = 0.00497\ m^3/kg$, $P_1 = 3836.9$ kPa

State 2: $v_2 = 0.8\ v_1 = 0.00398\ m^3/kg = v_g$ ⇨ linear interpolation

$$T = \mathbf{65.04°C} = 65 + 5\ (0.00398 - 0.00399)/(0.00286 - 0.00399)$$
$$= 65 + 5 * 0.00885$$

$$P = 4278.3 + 0.00885\ (4763.1 - 4278.3) = \mathbf{4282.6\ kPa}$$



R2.15

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?

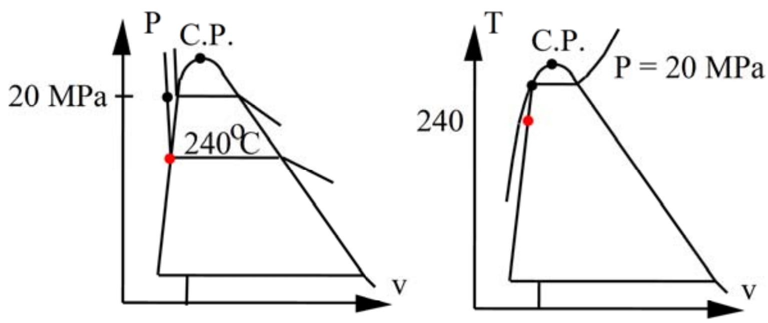
Solution:

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

$\dot{m} = \dot{V}/v = 0.05 \text{ m}^3 / 0.001205 \text{ m}^3/\text{kg} = \mathbf{41.5 \text{ kg/s}}$

$v_{f\,(240°C)} = 0.001229 \text{ m}^3/\text{kg} \Rightarrow \dot{m} = 40.68 \text{ kg/s}$ **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 saturated liquid at T is the best approximation if the compressed liquid table is not available and shown by the red dot.

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.

Ideal Gas Law

R2.16

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

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

ethanol: $R = \frac{\bar{R}}{M} = \frac{8.3145}{46.069} = 0.18048 \text{ kJ/kgK}$ same as Table A.5

R2.17

You are inflating a car tire to a gage pressure of 250 kPa. The process goes so slowly that the temperature is nearly constant equal to ambient 20°C. If the tire has a final inside volume of 0.1 m^3 how much air mass is there?

Solution:

Assume the air is an ideal gas and that ambient pressure is 100 kPa

$$P_2 = P_0 + \Delta P = 100 + 250 = 350 \text{ kPa}$$

$$m = \frac{PV}{RT} = \frac{350 \text{ kPa} \times 0.1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times 293.15 \text{ K}} = 0.416 \text{ kg}$$

R2.18

Air in an internal combustion engine has 227°C, 1000 kPa with a volume of 0.1 L. Combustion heats it to 1800 K in a constant volume process. What is the mass of air and how high does the pressure become? Is the air still an ideal gas at the final state?

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

$$m = \frac{P_1V_1}{RT_1} = \frac{1000 \text{ kPa} \times 0.1 \text{ m}^3}{0.287 \text{ kJ/kgK} \times (227 + 273) \text{ K}} = \mathbf{0.697 \text{ kg}}$$

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

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

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

This pressure is close to the critical pressure (N2, O2) but the T is high

$$P \approx P_c \quad \text{and} \quad T > 10\, T_c$$

so it could be close to ideal gas. We can check if pure nitrogen,

Tbl. B.6.2 at 3000 kPa, 1000 K

$$Z = \frac{Pv}{RT} = \frac{3000 \text{ kPa} \times 0.09996 \text{ m}^3\text{/kg}}{0.2968 \text{ kJ/kg-K} \times 1000 \text{ K}} = 1.01 \quad \text{very close}$$

R2.19

A propane tank of 1 m^3 is at 150 kPa, 300 K and connected by a valve to another tank of 0.5 m^3 with propane at 250 kPa, 380 K. The valve is opened and the two tanks come to a uniform state at 320 K. What is the final pressure?

Solution:

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

$$m_A = \frac{P_A V_A}{RT_A} = \frac{150 \text{ kPa} \times 1 \text{ m}^3}{0.1886 \text{ kJ/kgK} \times 300 \text{ K}} = 2.651 \text{ kg}$$

$$m_B = \frac{P_B V_B}{RT_B} = \frac{250 \text{ kPa} \times 0.5 \text{ m}^3}{0.1886 \text{ kJ/kgK} \times 380 \text{ K}} = 1.744 \text{ kg}$$

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

$$m_2 = m_A + m_B = (2.651 + 1.744) \text{ kg} = 4.395 \text{ kg}$$

$$P_2 = \frac{m_2 R T_2}{V_2} = \frac{4.395 \text{ kg} \times 0.1886 \text{ kJ/kgK} \times 320 \text{ K}}{1.5 \text{ m}^3} = \mathbf{176.8 \text{ kPa}}$$

Compressibility Factor

R2.20

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

For the saturated states we can use Fig. D.1 with the estimates

$$Z_f = 0.02, \qquad Z_g = 0.9$$

so

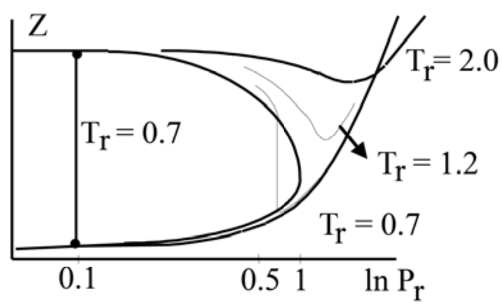
$$v_g/v_f = (ZRT/P)_g \,/\, (ZRT/P)_f = Z_g/Z_f = \frac{0.02}{0.9} = \mathbf{0.0222}$$

Table D.3 list the entries more accurately than we can read the figure

$$Z_f = 0.017, \qquad Z_g = 0.897$$

so

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



R2.21

Refrigerant R-32 is at -10 ^oC 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

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

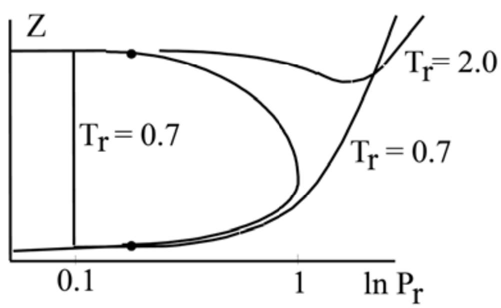
From Table D.4 or Figure D.1, $Z_f \approx 0.029$; $Z_g \approx 0.86$; $P_{r\,sat} \approx 0.16$

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

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

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

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



Equations of State

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

R2.22

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

Nitrogen from table A.2: $T_c = 126.2$ K, $P_c = 3390$ kPa,
$T_r = T/T_c = 160/126.2 = 1.26783$

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

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

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

The equation is:

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

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

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

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

R2.23

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

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

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

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

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

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

The equation is:

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

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

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

$v = 0.0035$ m^3/kg ⇨ $P = 9772.8$ kPa so v smaller

$v = 0.0033$ m^3/kg ⇨ $P = 10044.7$ kPa so v larger

$v = 0.0034$ m^3/kg ⇨ $P = 9906.5$ kPa

linear interpolation gives

$v =$ **0.00333 m^3/kg** ⇨ $P = 10002.7$ kPa OK.

Review Problems

R2.24

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

Solution:

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

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

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

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

b. $H_2O \qquad T = 400°C \qquad v = 0.2\ m^3/kg \qquad T > T_c$ so **superheated vapor**

Table B.1.3 between 1400 kPa and 1600 kPa:

$$P = 1400\ \text{kPa} + 200\ \text{kPa}\ \frac{0.2 - 0.2178}{0.19005 - 0.2178} = \mathbf{128.3\ kPa}$$

x = undefined

c. R-410A $T = -5\ °C \qquad P = 700$ kPa

compressed liquid ($P > P_g = 678{,}9$ kPa at -5°C) **x undefined**

Table B.4.1: $\quad v \approx \mathbf{0.000841\ m^3/kg}$

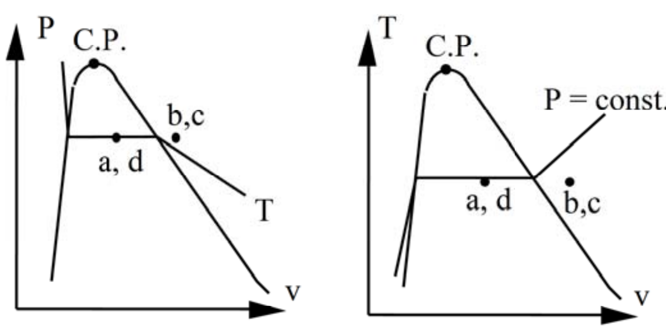
d. R-134a $P = 294$ kPa, $\quad v = 0.05\ m^3/kg$

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

two-phase $\qquad T = T_{sat} = 0°C$

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

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



R2.25

Determine the phase of the following substances and find the values of the unknown quantities.

(a) Water, P = 100 kPa, -10°C, v = ?
P = 500 kPa, 140°C, v = ?

(b) Air, T = 100°C, v = 0.500 m^3/kg, P = ?

(c) R-410A, T = 25°C, v = 0.01 m^3/kg, P = ?, h = ?

Solution:

(a) B.1.5 at -10°C: v = 0.0010891 m^3/kg; P > Psat so compressed solid
B.1.1 at 140 C: P > Psat =361 kPa so compressed liq.
B.1.4 at 500 kPa, 140°C: v = 0.001080 m^3/kg same as sat liq 140°C

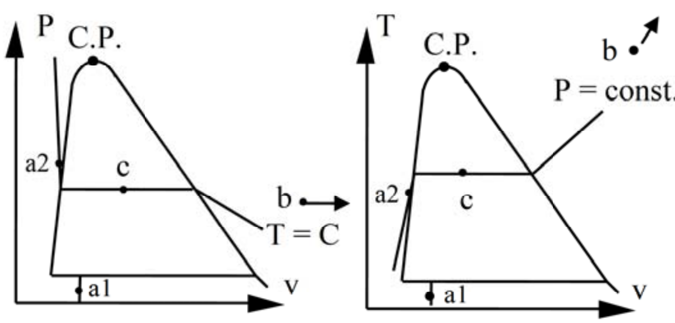
(b) Ideal gas, $P = RT/v = 0.287\text{ kJ/kgK} \times 373.15\text{ K}/0.5\text{ m}^3\text{/kg} = 214.2\text{ kPa}$

(c) B.4.1 at 25°C, $v_f = 0.000944$, $v_g = 0.01514$, $v_f < v < v_g$: saturated.

$$P = 1653.6\text{ kPa}, \qquad x = \frac{v - v_f}{v_{fg}} = \frac{0.01 - 0.000944}{0.01420} = 0.63775,$$

$$h = h_f + x\, h_{fg} = 97.59 + 0.63775 \times 186.43 = 216.48\text{ kJ/kg}$$

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



R2.26

Answer the following questions

(a) R-134a, $T = -20°C$, $u = 220$ kJ/kg, $P = ?$, $x = ?$

(b) Ammonia, $T = -20°C$, $v = 1.0\ m^3/kg$, $P = ?$, $x = ?$

(c) A spherical balloon contains air and maintains a pressure that is proportional to its diameter (e.g., $P = C \times D$, where D is diameter and C is a constant). What specific work is done by the air if it is heated from temperature T_1 to temperature T_2? Express your answer in terms of T_1, T_2, and physical constants associated with the air.

Solution:

(a) B.5.1 at –20°C: $u_f < u < u_g$ ⇨ 2-phase $P = P_{sat} = 133.7$ kPa.

$x = (u – u_f)/u_{fg} = (220 – 173.65)/192.85 = 0.2403$

(b) B.2.1, $v > v_g$ ⇨ superheated vapor found between 100 and 150 kPa at –20°C

x = undefined

Interpolate: $P = 100\ kPa + 50\ kPa\ (1 – 1.2101)/(\ 0.7977 – 1.2101) = 125.47\ kPa$

Comment: For a gas the interpolation should be done inversely in v for more accuracy.

c) $P = C\ D = \tilde{C}\ V^{1/3}$ Sphere: $V \sim D^3$

so **polytropic with n = –1/3**

$$ {}_1w_2 = \frac{1}{1 - n}(P_2v_2 - P_1v_1) = \frac{R}{1 - n}(T_2 - T_1) = \frac{3}{4} R\ (T_2 - T_1) $$

R2.27

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

Solution:

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

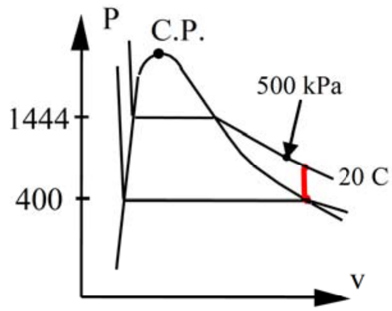
Process: cool to -20°C at constant v, so we assume saturated vapor

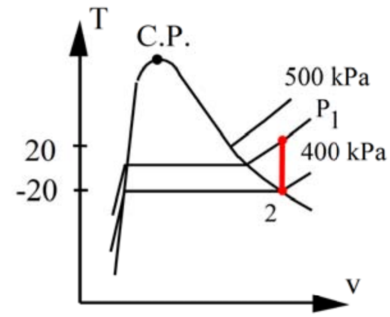
State 2: $v_2 = v_{g\text{ at -20°C}} = 0.06480\ m^3/kg$

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

interpolate between 400 and 500 kPa in Table B.4.2

=> $\mathbf{P_1 = 485\ kPa}$





R2.28

A cylinder has a thick piston initially held by a pin as shown in Fig. R2.28. 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**

R2.29E

Water at 80 F can exist in different phases dependent on the pressure. Give the approximate pressure range in lbf/in^2 for water being in each one of the three phases, vapor, liquid or solid.

Solution:

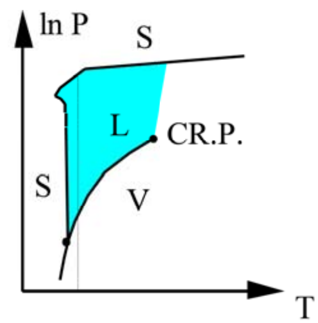
The phases can be seen in Fig. 2.4, a sketch of which is shown to the right.

T = 80 F = 540 R = 300 K

From Fig. 2.4:

$P_{VL} \approx 4 \times 10^{-3}$ MPa = 4 kPa = 0.58 psia,

$P_{LS} = 10^3$ MPa = 145 038 psia



0 < P <	**0.58 psia**	**VAPOR**
0.58 psia	**< P < 145 038 psia**	**LIQUID**
	P > 145 038 psia	**SOLID(ICE)**

English Unit Problems

R2.30E

Determine the missing property (of P, T, v, and x if apllicable) for water at

a. 680 lbf/in.^{2}, 0.03 ft^3/lbm

b. 150 lbf/in.^{2}, 320 F

c. 400 F, 3 ft^3/lbm

Solution: All cases can be seen from Table F.7.1

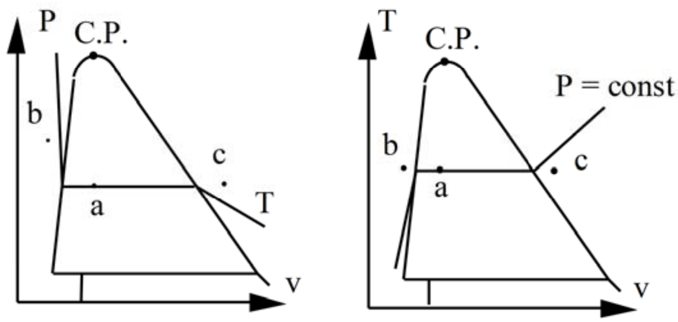
a. 680 lbf/in.^{2}, 0.03 ft^3/lbm

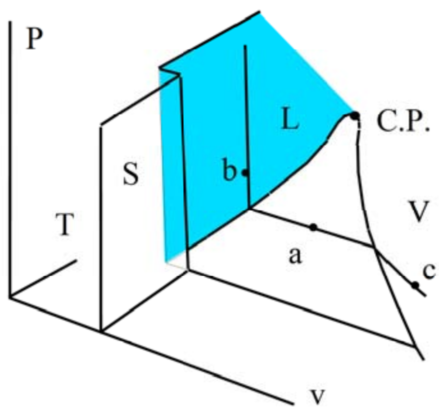
v_g = **0.2183**, v_f = **0.02472** ft^3/lbm, so **liquid + vapor mixture**

b. 150 lbf/in.^{2}, 320 F: **compressed liquid** $P > P_{sat}(T)$ = **89.6 lbf/in^2**

c. 400 F, 3 ft^3/lbm: **sup. vapor** $v > v_g(T)$ = **2.339** ft^3/lbm

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





R2.31E

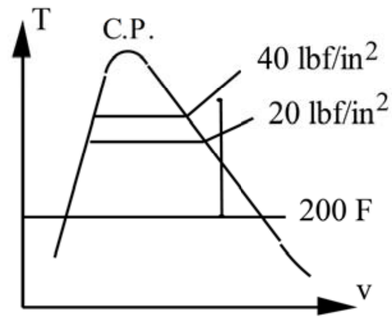
A sealed rigid vessel has volume of 35 ft^3 and contains 2 lbm of water at 200 F. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 400 F?

Solution:

Process: v = V/m = constant

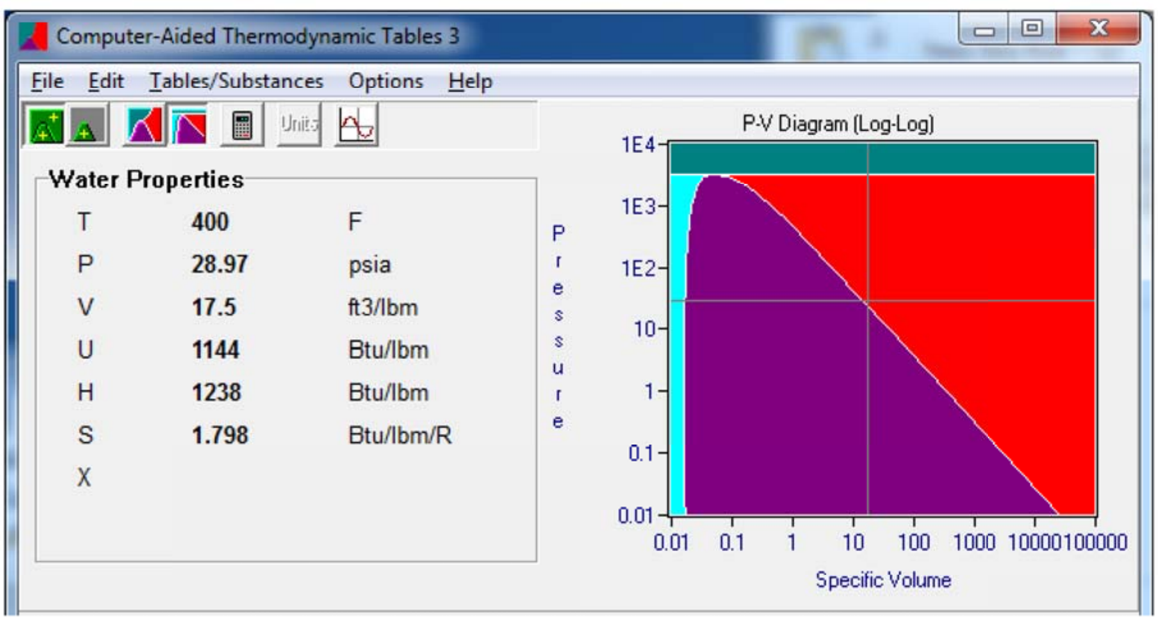
State 1: $v_1 = 35/2 = 17.5$ ft^3/lbm
from Table F.7.1
it is 2-phase

State 2: 400°F, 17.5 ft^3/lbm
Table F.7.2 between 20
and 40 lbf/in^2 so interpolate



$$P \cong 20 + (40 - 20)\,\frac{17.5 - 25.427}{12.623 - 25.427} = \mathbf{32.4\ lbf/in^2}$$

(The result is 28.97 psia if found by the software, i.e. linear interpolation is not so accurate)



R2.32E

A boiler feed pump delivers 100 ft^3/min of water at 400 F, 3000 lbf/in.^{2}. What is the mass flowrate (lbm/s)? What would be the percent error if the properties of saturated liquid at 400 F were used in the calculation? What if the properties of saturated liquid at 3000 lbf/in.^{2} were used?

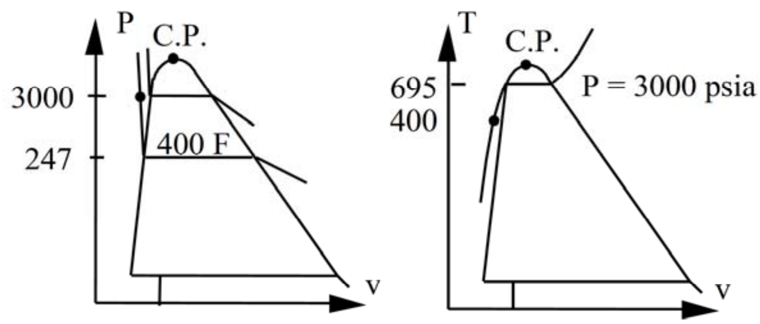
Solution:

Table F.7.3: $v = 0.0183\ ft^3/lbm$ (interpolate 2000-8000 psia)

$$\dot{m} = \frac{\dot{V}}{v} = \frac{100}{60 \times 0.018334} = 91.07 \text{ lbm/s}$$

$$v_{f\,(400\,F)} = 0.01864\ ft^3/lbm \;\Rightarrow\; \dot{m} = 89.41 \text{ lbm/s} \;\; \textbf{error 1.8\%}$$

$$v_{f\,(3000\,lbf/in^2)} = 0.03475\ ft^3/lbm \;\Rightarrow\; \dot{m} = 47.96 \text{ lbm/s} \;\; \textbf{error 47\%}$$

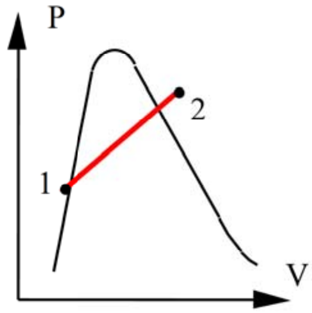


The constant T line is nearly vertical for the liquid phase in the P-v diagram. The state is at so high P, T that the saturated liquid line is not extremely steep.

R2.33E

Water in a piston/cylinder is at 100 F, 14.7 psia, and the piston loading is such that pressure is linear in volume, $P = A + BV$. Heat is now added until it reaches a state of 400 F, 200 psia. Find the final specific volume and sketch the process in a P-v diagram.

Solution:



State 1: Table F.7.1: $v_1 = 0.01613$ ft^3/lbm

Check state 2 in Table F.7.1

$P_2 < P_{sat} = 347$ psia so superheated vapor

F.7.2: $v = 2.3609$ ft^3/lbm

R2.34E

Give the phase and the specific volume for each of the following.
Solution:

a. CO_2 $\quad T = 510$ F $\quad P = 75$ lbf/in.^{2} Table F.4

superheated vapor ideal gas

$$v = RT/P = \frac{35.1 \text{ ft-lbf/lbm-R} \times (510 + 459.7) \text{ R}}{75 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$$

$= \mathbf{3.152\ ft^3/lbm}$

b. Air $\quad T = 68$ F $\quad P = 2$ atm $\quad$ Table F.4

superheated vapor ideal gas

$$v = RT/P = \frac{53.34 \text{ ft-lbf/lbm-R} \times (68 + 459.7) \text{ R}}{2 \times 14.6 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$$

$= \mathbf{6.6504\ ft^3/lbm}$

c. Ar $T = 300$ F, $P = 30$ lbf/in.^{2} $\quad$ Table F.4

Ideal gas: $\quad v = RT/P = \dfrac{38.68 \text{ ft-lbf/lbm-R} \times (300 + 459.7) \text{ R}}{30 \text{ lbf/in.}^2 \times 144 \text{ (ft/ in.)}^2}$

$= \mathbf{6.802\ ft^3/lbm}$

R2.35E

Calculate the ideal gas constant for argon and hydrogen based on Table F.1 and verify the value with Table F.4

The gas constant for a substance can be found from the universal gas constant from table A.1 and the molecular weight from Table F.1

Argon: $$R = \frac{\bar{R}}{M} = \frac{1.98589}{39.948} = \mathbf{0.04971\ \frac{Btu}{lbm\ R}} = \mathbf{38.683\ \frac{lbf\text{-}ft}{lbm\ R}}$$

Hydrogen: $$R = \frac{\bar{R}}{M} = \frac{1.98589}{2.016} = \mathbf{0.98506\ \frac{Btu}{lbm\ R}} = \mathbf{766.5\ \frac{lbf\text{-}ft}{lbm\ R}}$$

Recall from Table A.1: 1 Btu = 778.1693 lbf-ft

R2.36E

Air in an internal combustion engine has 440 F, 150 psia with a volume of 2 ft^3. Now combustion heats it to 3000 R in a constant volume process. What is the mass of air and how high does the pressure become?

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

$$m = \frac{P_1V_1}{RT_1} = \frac{150 \text{ psia} \times 60 \text{ in}^3 \quad (1/12) \text{ ft/in}}{53.34 \text{ ft-lbf/lbm-R} \times (440 + 459.67) \text{ R}} = \mathbf{0.0156\ lbm}$$

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

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

$$P_2 = P_1 \times T_2/T_1 = 150 \text{ psia} \times \frac{3000}{440 + 459.67} = \mathbf{500.2\ psia}$$

P is close to critical P for nitrogen but lower than that of oxygen.
T is 4 times critical T for nitrogen so it is **still an ideal gas**.

R2.37E

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

Solution:

a. R-410A at $T = 50$ F, $v = 0.4$ ft^3/lbm: Table F.9.1: $v > v_g = 0.3818$ ft^3/lbm

sup. vap. F.9.2 interpolate between sat. and sup. vap at 50 F.

Find v at 150 psia, 50 F: v = 0.4066

Now interpolate between the sat vap 157.473 psia and the 150 psia.

$P \cong 150 + 7.473\ (0.4 - 0.4066)/(0.3818 - 0.4066) =$ **152 lbf/in^2**

b. H_2O $v = 2$ ft^3/lbm, $x = 0.5$: Table F.7.1

since v_f is so small we find it approximately where $v_g = 4$ ft^3/lbm.

$v_f + v_g = 4.3293$ at 330 F, $v_f + v_g = 3.80997$ at 340 F.

linear interpolation $T \cong$ **336 F**, $P \cong$ **113 lbf/in^2**

c. H_2O $T = 150$ F, $v = 0.01632$ ft^3/lbm: Table F.7.1, $v < v_f$

compr. liquid $P \cong$ **500 lbf/in^2**

d. NH_3 $T = 80$ F, $P = 13$ lbf/in.^{2} Table F.8.1 P < Psat

sup. vap. interpolate between 10 and 15 psia: v = **26.97 ft^3/lbm**

v is not linear in P (more like 1/P) so computer table is more accurate.

e. R-134a $v = 0.08$ ft^3/lbm, x = 0.5: Table F.10.1

since v_f is so small we find it approximately where $v_g = 0.16$ ft^3/lbm.

$v_f + v_g = 0.1729$ at 150 F, $v_f + v_g = 0.1505$ at 160 F.

linear interpolation $T \cong$ **156 F**, $P \cong$ **300 lbf/in^2**

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