Solution Manual
Chapter 2

Eleventh Edition

Fundamentals of Thermodynamics

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WILEY

August 2025

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In-Text Concept Questions

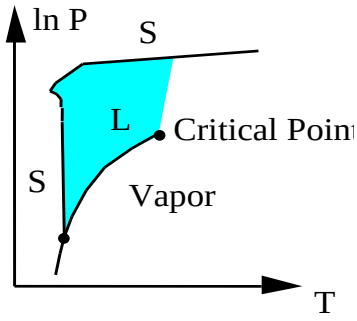
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2.a

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

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



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2.b

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

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

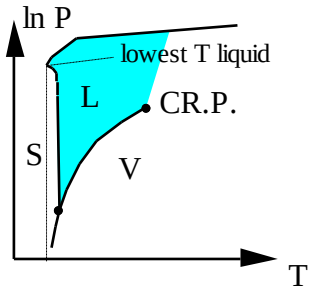
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2.c

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

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



T ≈ 255 K ≈ - 18°C

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2.d

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, P_{sat} = 475.9 kPa.

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2.e

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

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

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

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

The volumes are

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

$$y = V_g/V_{tot} = \frac{m_g\, v_g}{mv} = \frac{x\, v_g}{v} = \frac{0.5\, v_g}{0.5\, v_f + 0.5\, v_g} = \frac{v_g}{v_f + v_g} \approx 1$$

(it is slightly smaller than 1)

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

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2.f

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

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

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2.g

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

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

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

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

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2.h

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

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

From Table B.1.1 $v_f = 0.00100$ 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 porous material exposed to the weather on buildings, roads and mountains. It can burst water pipes and crack engine blocks (that is why you put anti-freeze in it).

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2.i

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

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

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

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

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

$$Z = Pv/RT = \frac{100 \text{ kPa} \times 1.55215 \text{ m}^3/\text{kg}}{0.5183 \text{ kJ/kg-K} \times 300 \text{ K}} = 0.998$$

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

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2.j

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

NO. You need a second property.

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

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2.k

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

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

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

The reduced temperature is:

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

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

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

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Concept Problems

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2.1

Are the pressures in the tables absolute or gauge pressures?

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

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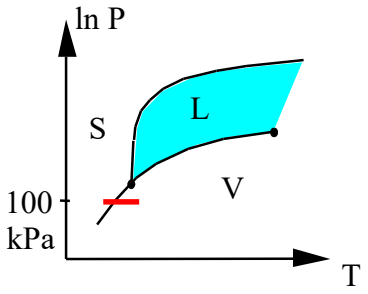
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2.2

What is the minimum pressure for liquid carbon dioxide?

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

The 100 kPa is below the triple point.



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2.3

When you skate on ice, a thin liquid film forms under the skate; why?

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

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

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

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2.4

Is it possible to have water vapor at -5^{o}C?

This T is below the triple point (0.01^{o}C) and there cannot be any liquid present. However for very small pressures (super vacuum) where $P < P_{sat} \approx 0.4$ kPa from Table B.1.5 we can have cold water vapor. See also Fig. 2.4.

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2.5

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

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

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2.6

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

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

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2.7

Can a vapor exist below the triple point temperature?

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

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2.8

Ice cubes can disappear and food can dry out (freezer burn) in the freezer. What happens to the ice?

When you open a refrigerator some warmer air comes in so if that heats the air over the ice cubes a small amount of ice will evaporate. Eventually the air will cool from where it is the coldest namely on the cooling coils with very cold refrigerant inside them. At that location some of the water vapor will turn back into frost on the coil. If the food is in a closed plastic bag you can see that some ice has formed on the inside surface of the plastic which is water coming from the food inside the bag and then being refrozen on the plastic inside surface. Recall that you cool the bag from the outside. Such cycling of the temperature eventually dries out the food.

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2.9

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

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

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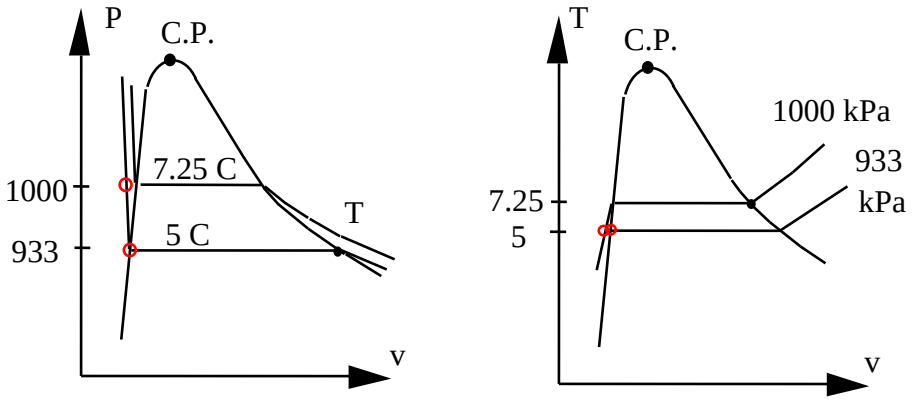
2.10

If I have 1 L of R-410A at 1 MPa, 5°C what is the phase?

R-410A Tables B.4:

B.4.1 P_{sat} = 933.9 kPa at 5°C so **compressed liquid**.

B.4.1 $v \approx v_f$ = 0.000870 m^3/kg at same T (5°C)



The open circle indicates table state used.

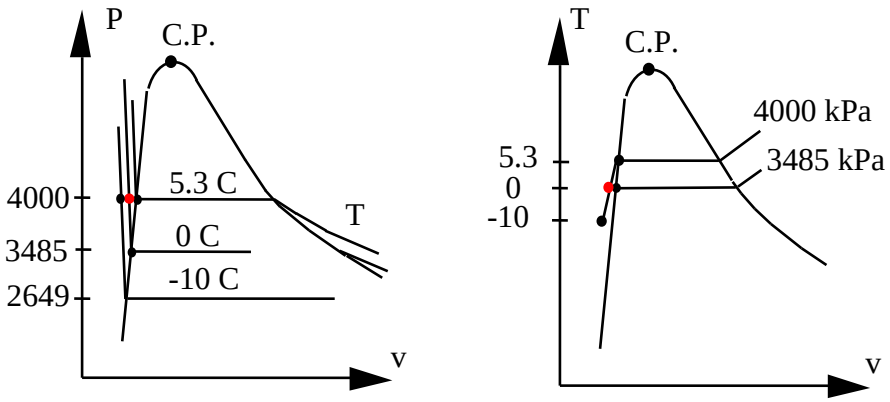
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2.11

Find the state of carbon dioxide at 4000 kPa, 0°C. Indicate in both the $P-v$ and $T-v$ diagrams the location of the nearest states listed in Table B.3.

Table B.3.1 at 0°C: P_{sat} = 3485.1 kPa < P => compressed liquid.
B.3.3 has state 4000 kPa, 0°C heading T_{sat} = 5.3°C



The red dot shows the state and the black dots are nearby table states

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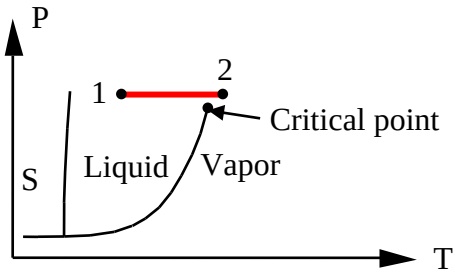
2.12

Water at 25 MPa, 25°C is heated to 400°C at constant P. Does it boil? Explain.

Table B.1.1 at 25°C: P_{sat} = 3.169 kPa << P

Table B.1.2 we see that P > P_C = 22089 kPa.

Beginning state is above the critical point as a compressed liquid but at high P.



So as we heat at constant P we move towards to vapor region into the dense gas and eventually at high T will approach ideal gas. State 2 is covered by Table B.1.3 but not listed (20 MPa and 30 MPa are listed).

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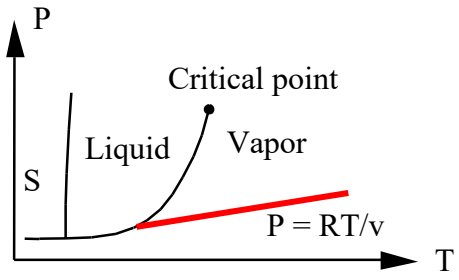
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2.13

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

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

Constant *v* is a straight line with slope (R/*v*) in the P-T diagram, the larger *v* is the lower the slope.



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2.14

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

Solution:

The equation for a liquid is: v = Constant = v_o

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

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2.15

Is saturated water vapor an ideal gas at 10 MPa? Is it at 10 kPa?

Table B.1.2 at 10 MPa: T = 311.06°C, v = 0.01803 m^3/kg

Pv = 10 000 kPa × 0.01803 m^3/kg = 180.3 kJ/kg
RT = 0.4615 kJ/kg-K × (273.15 + 311.06) K = 269.6 kJ/kg

Not ideal gas Pv ≠ RT:

$$Z = Pv/RT = 180.3/269.6 = 0.669$$

The volume is smaller than for an ideal gas but still much larger than a typical liquid volume.

Table B.1.2 at 10 kPa: T = 45.81°C, v = 14.67355 m^3/kg

Pv = 10 kPa × 14.67355 m^3/kg = 146.7 kJ/kg
RT = 0.4615 kJ/kg-K × (273.15 + 45.81) K = 147.2 kJ/kg

Now we see that Pv ≈ RT so really close to ideal gas

$$Z = Pv/RT = 146.7/147.2 = 0.997$$

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