

**Oblig03 — Fys2160 — 2016****Exercise 0.4.** Phase coexistence in the van der Waals system

**Learning outcomes.** In this project we will study the van der Waals fluid. You will learn how to find the Gibbs free energy for the system and how to use Gibbs free energy to find the equilibrium state of the system, also in the case when we have both a liquid and a gas phase in the system.

The van der Waals fluid is a mean field theory of a gas. It is a model system, just as the ideal gas, although it includes more features of realistic gases. The van der Waals gas includes two of the main effects of an attractive two-particle interaction between particles in the gas: a repulsive interaction that keeps particles apart, and an attractive long-range interaction that pulls particles together. These two effects leads to two changes in the Helmholtz free energy of the gas, as compared to an ideal gas: Instead of the volume  $V$  we introduce the effective volume,  $V - Nb$ , where the volume  $b$  is the excluded volume per particle, and we introduce an average binding energy,  $-a(N/V)^2$ . Helmholtz free energy for the van der Waals gas is:

$$F_{wdW} = -NkT \left( \ln \left( \frac{n_Q(V - Nb)}{N} \right) + 1 \right) - \frac{aN^2}{V}, \quad (0.21)$$

where  $n_Q(T) = (2\pi mkT/h^2)^{3/2}$  is a function of  $T$  only.

**a)** Show that the pressure,  $p(N, V, T)$ , of the van der Waals gas is

$$p = \frac{NkT}{V - Nb} - \frac{aN^2}{V^2}. \quad (0.22)$$

This is the equation of state for the van der Waals gas. We introduce the quantities

$$p_c = \frac{a}{27b^2}, \quad V_c = 3Nb, \quad kT_c = \frac{8a}{27b}, \quad (0.23)$$

so that we can introduce dimensionless quantities:

$$\hat{p} = p/p_c, \quad \hat{V} = V/V_c, \quad \hat{T} = T/T_c, \quad (0.24)$$

and similarly for the density

$$\hat{\rho} = 1/\hat{V} = \rho/\rho_c, \quad \rho_c = \frac{1}{3b}. \quad (0.25)$$

**b)** Show that the pressure of the van der Waals gas can be written as

$$\hat{p} = \frac{8\hat{T}}{3\hat{V} - 1} - \frac{3}{\hat{V}^2}. \quad (0.26)$$

c) Plot the pressure  $\hat{p}$  as a function of  $\hat{V}$  for  $\hat{V}$  in the range from 0.4 to 20 for  $\hat{T} = 1.15, 1.0$ , and  $0.85$ .

Notice that the volume is not a unique function of the pressure for some range of values. This means that we generally cannot find  $\hat{V}(\hat{p})$ .

d) Show that the pressure also can be expressed using the density instead of the volume:

$$\hat{p} = \frac{8\hat{\rho}\hat{T}}{3-\hat{\rho}} - 3\hat{\rho}^2. \quad (0.27)$$

e) Plot the pressure  $\hat{p}$  as a function of  $\hat{\rho}$  for  $\hat{\rho}$  in the range from 0.0 to 2.0 for  $\hat{T} = 1.15, 1.0$ , and  $0.85$ .

f) Based on your plot, for what temperature does the density become non-unique function of the pressure?

g) Based on your plot, when does the isothermal compressibility

$$\kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial P} \right)_{T,N} = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial P} \right)_{T,N}, \quad (0.28)$$

become negative?

A negative compressibility would mean that the system was unstable. This is an unphysical situation. Let us now discuss the thermodynamic equilibrium and stability of the system by addressing the Gibbs free energy of the system.

h) Show that Gibbs free energy of the system in dimensional quantities is

$$G(T, V, N) = \frac{NkTV}{V - Nb} - \frac{2aN^2}{V} - NkT (\ln(n_Q(V - Nb)/N) + 1), \quad (0.29)$$

Unfortunately, we cannot insert  $V(p)$  into this relation to get  $G(T, p, N)$ , which are the natural variables for  $G$ , because  $V$  is not a unique function of  $p$ . Let us therefore instead study Gibbs free energy as a function of  $V$  as  $V$  is lowered. This gives a unique pressure  $p$  for every value of  $V$  even though the reverse is not true.

i) Argue that Gibbs free energy can be written as

$$G = -NkT \ln(V - Nb) - \frac{aN^2}{V} + pV + NkT c(T), \quad (0.30)$$

where  $c(T)$  is a function of temperature alone.

It is now convenient to introduce a dimensionless Gibbs free energy by introducing  $G_c = 3kT_c/8$ .

**j)** Show that Gibbs free energy per particle is

$$\hat{g} = \frac{G/G_c}{N} = -3\hat{\rho} - \frac{8}{3}\hat{T} \ln\left(\frac{3}{\hat{\rho}} - 1\right) + \frac{\hat{p}}{\hat{\rho}}, \quad (0.31)$$

if you only include terms that depend on  $\hat{p}$  or  $\hat{\rho}$ .

**k)** For  $\hat{T} = 0.9$  plot  $\hat{p}$  as a function of  $\hat{\rho}$  for  $\hat{\rho}$  from 0.2 to 2.0. Then plot  $\hat{V}$  as a function of  $\hat{\rho}$  for the same data, using that  $\hat{V} = 1/\hat{\rho}$ . Finally, plot  $\hat{g}$  as a function of  $\hat{\rho}$  for the same data. Comment on the curve you get for Gibbs free energy. You may want to plot all three plots in three subfigures and highlight some points along the curves in order to be able to relate the values in the three plots.

**l)** Argue that we can find the minimum of Gibbs free energy if we can determine where the curve  $\hat{g}(\hat{\rho}(\hat{p}))$  intersects itself.

**m)** You can find self-intersections in matlab using the program `selfintersect`. When you call `selfintersect` for this particular dataset ( $\hat{T} = 0.9$ ), you will get a pair of indices. Plot the corresponding points - the two points corresponding to the intersection — in the plots for  $\hat{p}(\hat{\rho})$  and for  $\hat{V}(\hat{\rho})$ . Draw a straight line between the two points. Comment on the results.

**n)** What do you think really happens in the system between the two intersections?

**o)** Make a systematic study, where you plot the line between the two intersection points in the  $\hat{p}(\hat{V})$  plots for  $\hat{T}$  varying from 1.0 down to 0.85. Comment on (or simply marvel at) the results.