LIQUEFYING GASES: THE HAMPSON-LINDE CYCLE

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Reference: Daniel V. Schroeder, *An Introduction to Thermal Physics*, (Addison-Wesley, 2000) - Problem 4.33.

To liquefy a gas such as nitrogen, a cycle similar to the refrigeration cycle discussed in an earlier post is used, except that the gas to be liquefied is itself the working fluid. A common technique for liquefying most gases (except those with very low boiling points such as hydrogen and helium) is the Hampson-Linde cycle. A compressor increases the pressure of the gas (initially at room temperature, say) which is then throttled to a much lower pressure. The throttling decreases the temperature, but typically does not liquefy the gas on the first pass. The cooled gas is then passed through a heat exchanger where it absorbs some heat from the high-pressure gas before the latter is throttled. This gives the high-pressure gas a lower temperature *before* it is throttled which in turn means that its temperature *after* throttling is lower than was achieved after throttling the gas on the first pass. The cycle continues, achieving successively lower temperatures on each pass until after throttling, the temperature is lowered enough that some of the gas liquefies. At this point, some extra gas is introduced into the system to replace the gas that has liquefied.

We can work out how much the temperature drops in the throttling process in the same way as for a refrigerator, if we have enthalpy tables for the gas concerned. Schroeder gives some data for nitrogen in his Table 4.5, at pressures of 1 bar and 100 bars. At 1 bar, nitrogen's boiling point is 77 K, so the enthalpies for both the liquid and gas states are given for this temperature and pressure; for other points, only the enthalpy of the gas is given.

It may seem curious that some of the enthalpies given are negative. I believe the reason for this is that the enthalpies are given relative to some reference state (which isn't specified). However, in practice, only enthalpy differences matter, so this shouldn't cause a problem.

Suppose we set up a system to liquefy nitrogen by operating between pressures of 100 bars and 1 bar, and that we start with a temperature of 300 K (roughly room temperature) at a pressure of 100 bars. From Table 4.5, the enthalpy (per mole) is 8174 J. After throttling to 1 bar, we can find the final temperature by interpolating as usual. First, we observe that the

1

temperature lies between 200 K and 300 K (since the enthalpies at 1 bar for these two temperatures bracket 8174 J). We get

$$8174 \;=\; 5800x + 8717\,(1-x) \tag{1}$$

$$x \;=\; 0.186 \tag{2}$$

The final temperature is therefore

$$T = 200x + 300\,(1-x) = 281.4 \text{ K} \tag{3}$$

After a few more cycles, suppose the temperature is reduced to 200 K. At this point, the entropy at 100 bars is 4442 J, which is bracketed at 1 bar by the enthalpies at 100 K and 200 K. As above:

$$4442 \;=\; 2856x + 5800\,(1-x) \tag{4}$$

$$x \;=\; 0.461 \tag{5}$$

The final temperature is therefore

$$T \;=\; 100x + 200\,(1-x) = 153.9 \text{ K} \tag{6}$$

Now suppose we start at a temperature of 100 K at 100 bars. The enthalpy here is -1946 J, which lies between the enthalpies for liquid and gaseous nitrogen at 77 K and 1 bar, so after throttling, the temperature will be 77 K and some of the nitrogen will liquefy. To find the fraction x that is liquid, we interpolate as usual:

$$-1946 \;=\; -3407x + 2161\,(1-x) \tag{7}$$

$$x \;=\; 0.738 \tag{8}$$

The highest temperature at which some liquefaction occurs is the temperature at 100 bars that has an enthalpy equal to the enthalpy of the gas at 77 K and 1 bar, which is 2161 J. On the line in the table for 100 bars, this lies between temperatures of 100 K and 200 K, so we have

$$2161 \;=\; -1946x + 4442\,(1-x) \tag{9}$$

$$x \;=\; 0.357 \tag{10}$$

$$T \;=\; 100x + 200\,(1-x) = 164.3 \text{ K} \tag{11}$$

Finally, at very high temperatures such as 600 K, the enthalpy at 100 bars is actually larger than the enthalpy at 1 bar. If we throttled nitrogen at 100 bars and 600 K, this means that the temperature after throttling would actually increase.

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