Sage Model Notes

ExpanderCapillaryChoked.ltc

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A model for the expansion process in a vapor-compression refrigeration cycle, where a liquid refrigerant at 50 C at the exit of a condenser heat exchanger expands within a capillary tube to mostly vapor (by volume) at -10 C at the entrance of an evaporator heat exchanger:

evaporator   capillary   condenser
entrance   exit
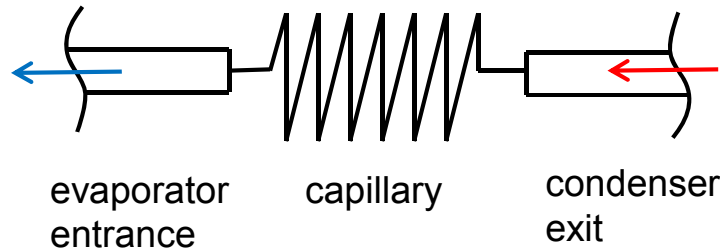
This is the Sage model:
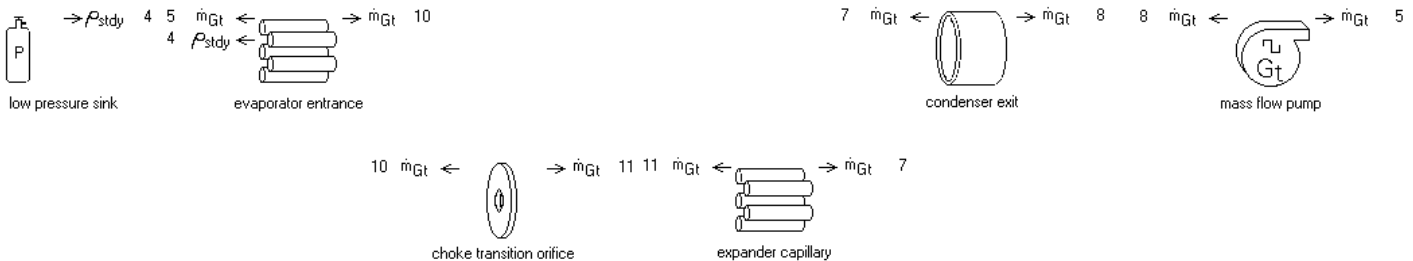
The *low pressure sink* determines the evaporator pressure according to the saturation pressure for the refrigerant and the desired evaporator temperature. In this case the refrigerant (Gas input) is isobutane (R 600a) with a saturation pressure of 1.1 bar at -10 C. The *mass flow pump* provides a negative (directed toward left) flow with the mass flow rate input chosen to produce a pressure-drop through the *expander capillary* and *choke transition orifice* so that the pressure on the condenser side is the saturation pressure at the condenser temperature. In this case, 6.8 bar at 50 C. In theory you could replace the *mass flow pump* with a *pressure-regulated compressor* to directly set the pressure drop but the solution using a *mass flow pump* seems to converge more reliably.

On the pressure-enthalpy diagram below the expansion is the process 3-4. Assuming expansion is isenthalpic (negligible heat transfer through capillary walls) the vapor quality (curves within two-phase region) after expansion will be about X = 0.4. In other words 40% vapor by mass. That does not sound like mostly vapor, but the density of the liquid (510 kg/m^3) is about 170 times higher than the vapor (3.05 kg/m^3) so it turns out that the vapor is more than 99% of the total fluid volume. So volume-wise, it is mostly vapor exiting the expansion capillary.

5: Pressure vs. Enthalpy plot: isobutane

Enthalpy (kJ/kg)
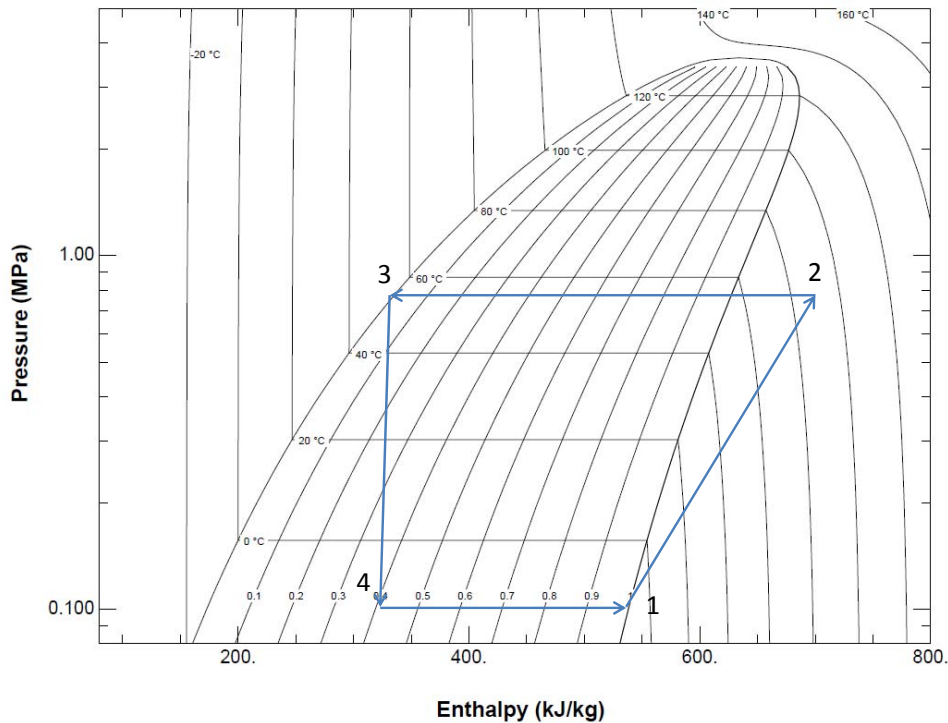
The math behind the quality-volume relationship starts with the definition of vapor quality as the fraction of vapor mass to total mass (vapor + liquid):

$$X = \frac{m_V}{m_V + m_L}$$

So,

$$\frac{1}{X} = 1 + \frac{m_L}{m_V} = 1 + \frac{\rho_L V_L}{\rho_V V_V}$$

And after some algebra

$$\frac{V_V}{V_L} = \frac{\rho_L}{\rho_V} \frac{X}{1 - X}$$

Choked Flow

The addition of a sharp-edged orifice at the low-pressure exit of the capillary is critical for achieving solution convergence. Without the orifice, the capillary flow velocity accelerates to the sonic velocity at the exit and the pressure cannot decrease further to the low-pressure sink pressure — the flow is choked. The sharp-edged orifice is the only Sage component capable of dealing with choked flow. It imposes a pressure drop into the solution, corresponding to the shock-boundary expansion of the sonic flow leaving the orifice at the capillary exit pressure. In the model the pressure at the capillary exit is 2.2 bar. The remaining expansion from 2.3 bar to 1.1 bar occurs across the orifice.

Refrigerant Fluid

The working fluid of the model (Gas input) is Isobutane (R600A), which is not an option in the standard GasLTC.dta data file. If you want to investigate a different refrigerant you

will have to use the RefpropToSage utility to create a Sage property file (*.dta) from one of the refrigerants in the Refprop data base. There are so many possible refrigerants available that it is not practical to include each one in the GasLTC.dta file. You can then use the PropBase utility to add your refrigerant into the GasLTC.dta file or use the Options | Model Class dialog to select your individual refrigerant file as the gas property file.

The condenser pressure in the Sage model is a bit higher than the Refprop value of 6.8 bar. It is more like 7.4 bar. This is due to the artificial slope to pressure (as a function of specific volume) the Sage equation of state imposes in the two phase zone to improve convergence. By including more temperature data points below the critical temperature (TptsBelowTcrit input of RefpropToSage) you can reduce the discrepancy, although potentially at the expense of less reliable convergence. In this particular model it is not worth the effort because the condenser pressure is not especially critical. The main purpose of the model is to size the expansion capillary as a component in a refrigeration loop, so.