Sage Model Notes

LiquefyingJTLoop.scfn

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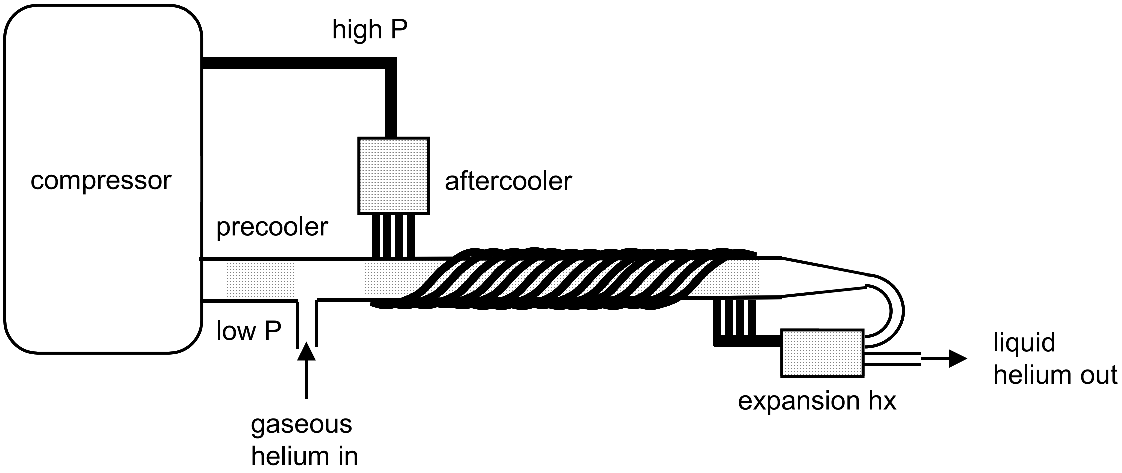
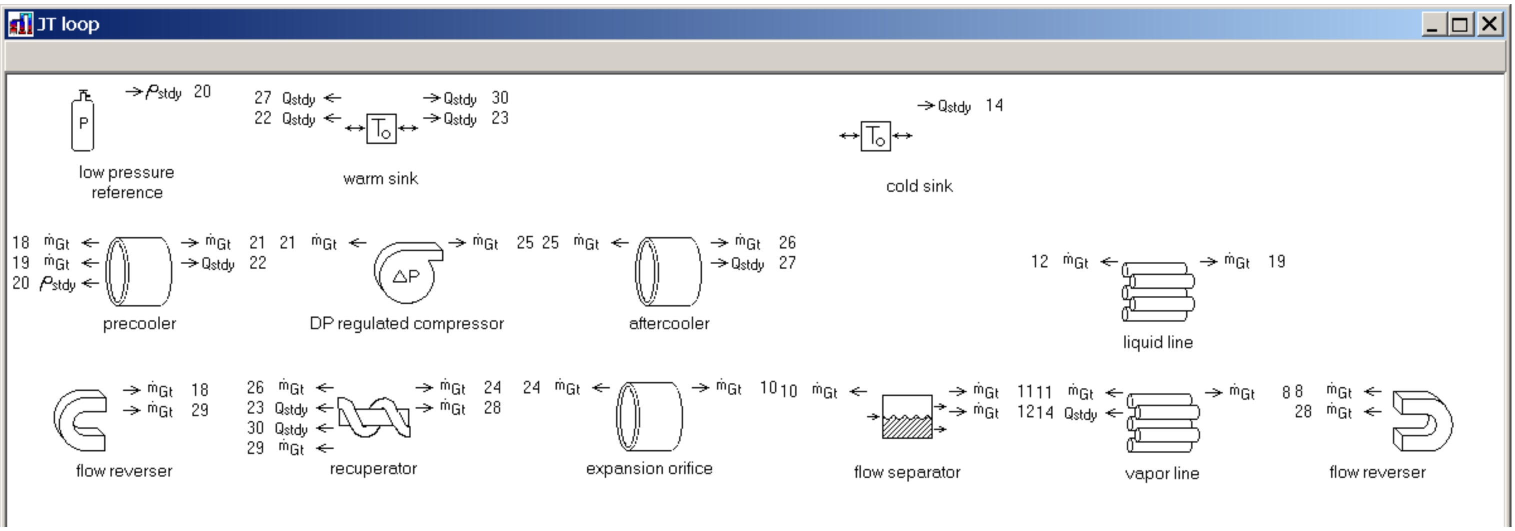
A model for a steady-state Joule-Thomson helium liquefier where gaseous helium at atmospheric pressure enters the device, undergoes the Joule-Thomson cooling cycle, and discharges as a steady stream of liquid helium at atmospheric pressure. Helium enters at 15 K and heat from the Joule-Thomson thermodynamic cycle (adiabatic compression heating) is rejected to a 15 K sink, pre-cooled by some means outside the scope of the model. The model is essentially the same as that of the non-liquefying Joule-Thomson cryocooler 6KJTLoop.ltc. The main difference from the viewpoint of hardware implementation is that there must be a provision for removing the liquefied helium at the cold end and adding the same mass flow rate of gaseous helium at the warm end to keep the system in equilibrium. Here is a schematic of the liquefier:



The Sage model looks like this:



The model employs many of the same basic components as the 6KJTLoop model. The documentation below discusses mainly the new components of this model and does not dwell on the basic components. For more information about the basic components see the documentation for the 6KJTLoop model.

The first thing to note about the present Sage model is that it is not actually an open cycle model like the physical hardware. Instead liquid helium production is vaporized and recycled internally. To make the model thermodynamically equivalent to the physical hardware the liquid helium is vaporized in a special *liquid line* component and re-enters the compressor via the left boundary of the *precooler*, bypassing the recuperator. Only the vapor part of the cold helium returns through the recuperator via the *vapor line*. In other words the *liquid line* heat exchanger represents an outside-world process where the liquid helium is used for some cooling purpose and vaporized in the process.

A description of the cooling cycle begins with the compressor. The *DP regulated compressor* provides a positive (directed toward right) high-pressure flow through the *aftercooler* then into the *high pressure tubes* of the *recuperator*. So far it is the same as the 6KJTLoop model except that the present model employs a *DP regulated compressor* instead of an *adiabatic compressor*. The difference is that the compressor pressure rise is an input and the mass flow rate an output, instead of the other way around. A *DP regulated compressor* avoids the problem of having too high a pressure rise if you specify mass flow rate too high.

After the *recuperator* the flow passes through the *expansion orifice* where the pressure drops from high to low and the Joule-Thomson cooling effect takes place. The *expansion orifice* is a packed particle bed like the 6KJTLoop model except instead of an active heat exchanger it is adiabatic bed. This allows to cold helium to emerge as a two-phase fluid as it enters the *flow separator*. The *flow separator* component is a special component of the Low-T Cooler model class that splits incoming two-phase flow into distinct gaseous and liquid streams that flow into the *vapor line* and *liquid line* respectively.

The *vapor line* is a heat exchanger with a conductive wall attached to the *cold sink*. Depending on the temperature of the *cold sink* there can be net cooling produced by the vapor line which corresponds to additional cooling provided by the physical hardware at the temperature of the *cold sink*. Flow leaving the *vapor line* reverses direction in a *flow reverser* and passes up the *low pressure tube* of the *recuperator*, pre-cooling the gas in the *high pressure tubes*, then returns to the compressor via another flow reverser and the *precooler*.

The *liquid line* is also a heat exchanger but with an isothermal wall that increases from 6 K to 15 K along the length. Its purpose is to vaporize any liquid helium production as discussed above. Flow leaving the *liquid line* does not return through the *recuperator* so no flow reversing is necessary. Instead the right boundary of the *liquid line* attaches directly to the left boundary of the *precooler*.

The *warm sink* anchors the temperatures of the *precooler* and *aftercooler* heat exchangers as well as the warm endpoint *tube wall* and *canister wall* temperatures of the *recuperator*.

The *cold sink* anchors only the temperature of the *vapor line* heat exchanger.

Bottom Line Outputs

User-defined variable *QcoldL* of the *cold line* component measures the cooling power produced by the vaporizing liquid helium. User-defined variable *QcoldV* of the *cold sink* measures the net cooling power extracted from the *cold sink* by the *vapor line* heat exchanger. The sum of the two is available in top-level user-defined variable *Q*. Adiabatic compressor power is available in top-level user-defined variable *Wcomp* and total heat rejection at the *warm sink* temperature in *Qwarm*.

Optimization

There is an optimization specification set up to essentially answer the question: How much liquid helium can you produce from 5 W compressor power input and an unlimited amount of pre-cooling at 15 K? The objective function is to maximize the liquid helium production as measured by output *QcoldL*. *Cold sink* temperature *T* is optimized subject to zero net cooling, effectively allowing the *cold sink* temperature to drop to the no-load temperature. Other optimized variables are the compressor pressure rise (FDP.Mean of *DP regulated compressor*) and the *Length* of the *expansion orifice.* Compressor power input is constrained to 5 W(*Wcomp* = -5.0).

Convergence

This is one of the more crotchety models when it comes to convergence. Especially when starting from an initialized state. The usual strategy of temporarily reducing the *FDP.Mean* input of the DP Regulated Compressor does not seem to help. Instead, the best strategy has been to adjust the normalization values of the root model:

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Lnorm           length scale (m)                        5.000E-03
FreqNorm        frequency scale (Hz)                    5.000E+00
Pnorm           pressure scale (Pa)                     1.000E+05
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Pnorm defines the initial pressure of the solution and the above value is the low-side pressure, which makes sense independently of convergence issues. Varying *Lnorm* and *FreqNorm* is more fruitful, with the above values producing convergence from a reinitialized model. The low value of *FreqNorm* is a bit unusual. For many models *FreqNorm* around 50 – 100 Hz seems to work best. This model seems to prefer *FreqNorm* around 10.

This being a steady-state model (*NTnode* = 1) the frequency input *Freq* is irrelevant. But *FreqNorm* is use to normalize solution variables like mass flow rate, velocity and many other quantities representing rates of change. So it is very relevant.