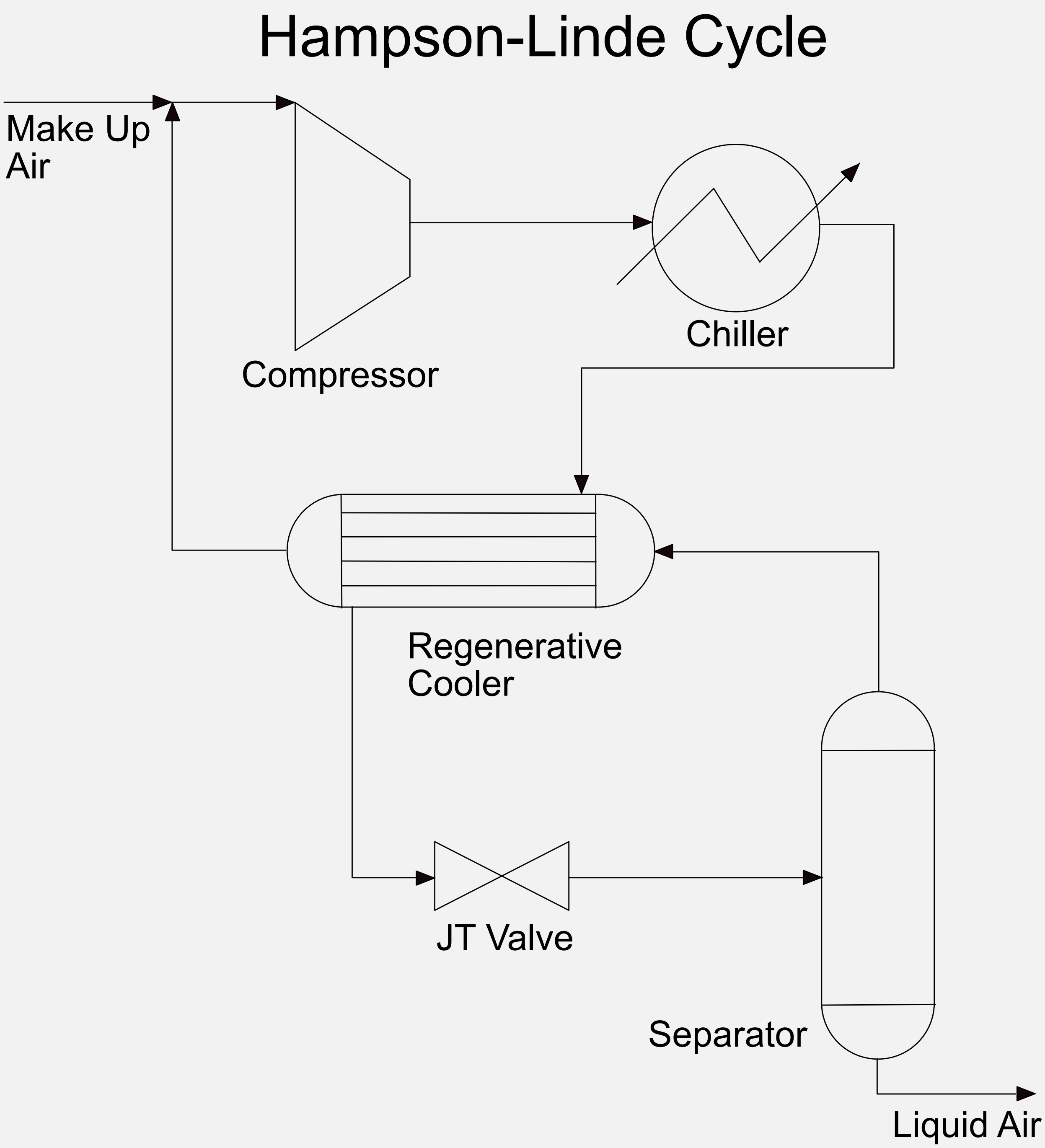
Hampson-Linde Air Liquifaction

The Hampson-Linde cycle is one of the first and simplest processes for liquifying air. Reproducing the thermodynamics of it here was an interesting exercise, but I must confess I more or less guessed at conditions and have no idea of the results accuracy. At the very least my ignoring any heat gained from the environment is a big simplification.

The diagram below shows basic process:



It is a pretty simple system, with air compressed to a high pressure, chilled by some external cooling, then further chilled in the regenerative cooler before being expanded to a low pressure through a valve. The Joule Thompson cooling through the valve results in partial liquification, which is the product stream. The cold vapour is passed through the other side of the renerative cooler to provide the cooling and then mixed with **MakeUpAir** before going back to the compressor.

The calculation starts with the **JTOutlet** flash, which the outlet of the JT valve and the inlet of the product separator. It is specified with the chosen low pressure, here 25 atm and a vapour fraction calculated as the fraction of the stream to be recycled (**recycleFrac**).

The total flow of **JTOutlet** will be the designated **productFlow** (100 kmol/h) divided by the liquid fraction.

The composition is trickier as it will consist of the steady state value resulting from mixing the vapour from the flash with the **MakeUpAir**. We know the make up air composition (assumed to just contain N2, O2 and Ar) and can start off by just estimating the same for **JTOutlet**.

A function **solver** is used to adjust the **JTOutlet** composition until it matches the composition of the mixed vapour and make up streams. The mole fractions for **JTOutlet** are specified with the formula:

MakeUpAir.x.b * 1.4 ^ solver.1

The **solver** output will initially be zeros, so the initial guess will just the **MakeUpAir** composition. The **solver** output will vary around 0, so the exponent form of the above equation is used to ensure the mole fractions can be made larger and smaller without ever becoming negative. As the calculated mole fractions are always normalized by the flash tool, we don't have to worry about values greater than 1.

Note that while **solver** only has a single function and output in this case, the function is an array of three values, as designated by the **nx** input in **solver**. This formula ensures the function has the same number of values as the **MakeUpAir** composition. Thus while there is only one function, the solver is in fact solving for multiple values, 3 in this case.

Before being mixed with the **MakeUpAir**, the vapour from the product separator goes through the regenerative cooler and its exit from that is represented by the flash **regenColdOut**. Its flow and composition are taken from the **JTOutlet** vapour phase, while its pressure drop is the **JTOutlet** pressure minus a small arbitrary amount. The temperature is calculated from a suitable temperature approach (5 degc) to the inlet fluid on the other side, namely **ChillerOutlet**.

It is the **regenColdOut** fluid that is mixed with the **MakeUpAir** in the **Mix2** model, the outlet of which is used in **CompError** to calculate the error values for the solver.

The inlet to the JT valve and hence also the warm side outlet of the regenerative cooler is represented by the flash **JTInlet**. Its pressure is taken as the warm side inlet pressure, from **ChillerOutlet**, minus a pressure drop. Its flow and composition are identical to **JTOutlet** and assuming the JT value is isenthalpic, its enthalpy is also identical to that of **JTOutlet**, which is enough to completely define it.

The **ChillerOutlet** represents the fluid leaving the external chiller and going to the regenerative cooler. This happens to be where the high pressure for the loop is set (75 atm). The temperature was set to 0 degc, assuming it would be chilled by something like a propane or ammonia refrigeration system (Linde assumed a warmer 10 degc brine).

To round things out, the compressor is modeled by **Compressor**, with its inlet being the flash **CompInlet**, which takes its values directly from the outputs of **Mix2**. Note that the only outlet used from **Compressor** is the outlet enthalpy, which is used to calculate the **ChillerDuty**. There is no need to actually have the loop closed inorder to calculate everything.

Looking inside the **Compressor** model reveals a problem though. CoolProp's flash fails for the flash tools when using the **Feed** thermo definition. However it can be made to solve by imposing the phase condition **supercritical** on it, which is done by appending **@supercritical** to the thermo definition (see the flash help).

It is **important** to ensure that the fluid will actually have the phase condition specified at the given conditions or invalid results could be produced. Looking at the phase envelope for **CompInlet** in the parent model, we can see the outlet fluid's temperature and pressure will be far above the phase envelope, so the outlet will indeed be supercritical.

However since the isenthalpic flash for **OutFluid** uses a search that could have been in a different region at some point, the **CheckOutlet** flash was added to compressor. It does a T and P flash at the **OutFluid** conditions and the **checkEnthalpies** expression checks to see if the enthalpies of the two flashes agree. If not, an alert would be displayed warning of the problem.

MakeUpAir

Label	Unit	B
q	Fraction	-1.00000
t	degC	40.00
p	kPa	2513.13
f	kmol/h	100.00
h	kJ/kmol	8936.76
s	kJ/kmol-K	172.99
dmolar	kmol/m^3	0.97
mwt	kg/kmol	28.96974
x	Nitrogen	0.78000
x	Oxygen	0.21000
x	Argon	0.01000

RecycleFrac	.8
ProductFlow	100 kmol/h

Solver

x (solved)	fx
-0.05865...[3,1]	5.648252e-6...[3,1]

ChillerOutlet

Label	Unit	B
q	Fraction	-1.00000
t	degC	0.00
p	kPa	7599.37
f	kmol/h	500.00
h	kJ/kmol	7360.11
s	kJ/kmol-K	157.26
dmolar	kmol/m^3	3.43
mwt	kg/kmol	28.76411
x	Nitrogen	0.82840
x	Oxygen	0.16320
x	Argon	8.399579e-3

regenColdOut

Label	Unit	B
q	Fraction	-1.00000
t	degC	-5.00
p	kPa	2513.12
f	kmol/h	400.00
h	kJ/kmol	7577.34
s	kJ/kmol-K	166.75
dmolar	kmol/m^3	1.14
mwt	kg/kmol	28.71268
x	Nitrogen	0.84051
x	Oxygen	0.15149
x	Argon	7.999570e-3

JTInlet

Label	Unit	B
q	Fraction	-1.00000
t	degC	-121.91
p	kPa	7579.37
f	kmol/h	500.00
h	kJ/kmol	1654.08
s	kJ/kmol-K	128.06

dmolar	kmol/m^3	12.40
mwt	kg/kmol	28.76411
x	Nitrogen	0.82840
x	Oxygen	0.16320
x	Argon	8.399579e-3

JTOutlet

Label	Unit	B	V	L
q	Fraction	0.80000	1.00000	0.00000
t	degC	-149.80	-149.80	-149.80
p	kPa	2533.12	2533.12	2533.12
f	kmol/h	500.00	400.00	100.00
h	kJ/kmol	1653.99	2251.96	-737.88
s	kJ/kmol-K	132.20	136.71	114.18
dmolar	kmol/m^3	4.93	4.14	20.47
mwt	kg/kmol	28.76411	28.71268	28.96985
x	Nitrogen	0.82840	0.84051	0.77997
x	Oxygen	0.16320	0.15149	0.21003
x	Argon	8.399579e-3	7.999570e-3	9.999614e-3

CompInlet

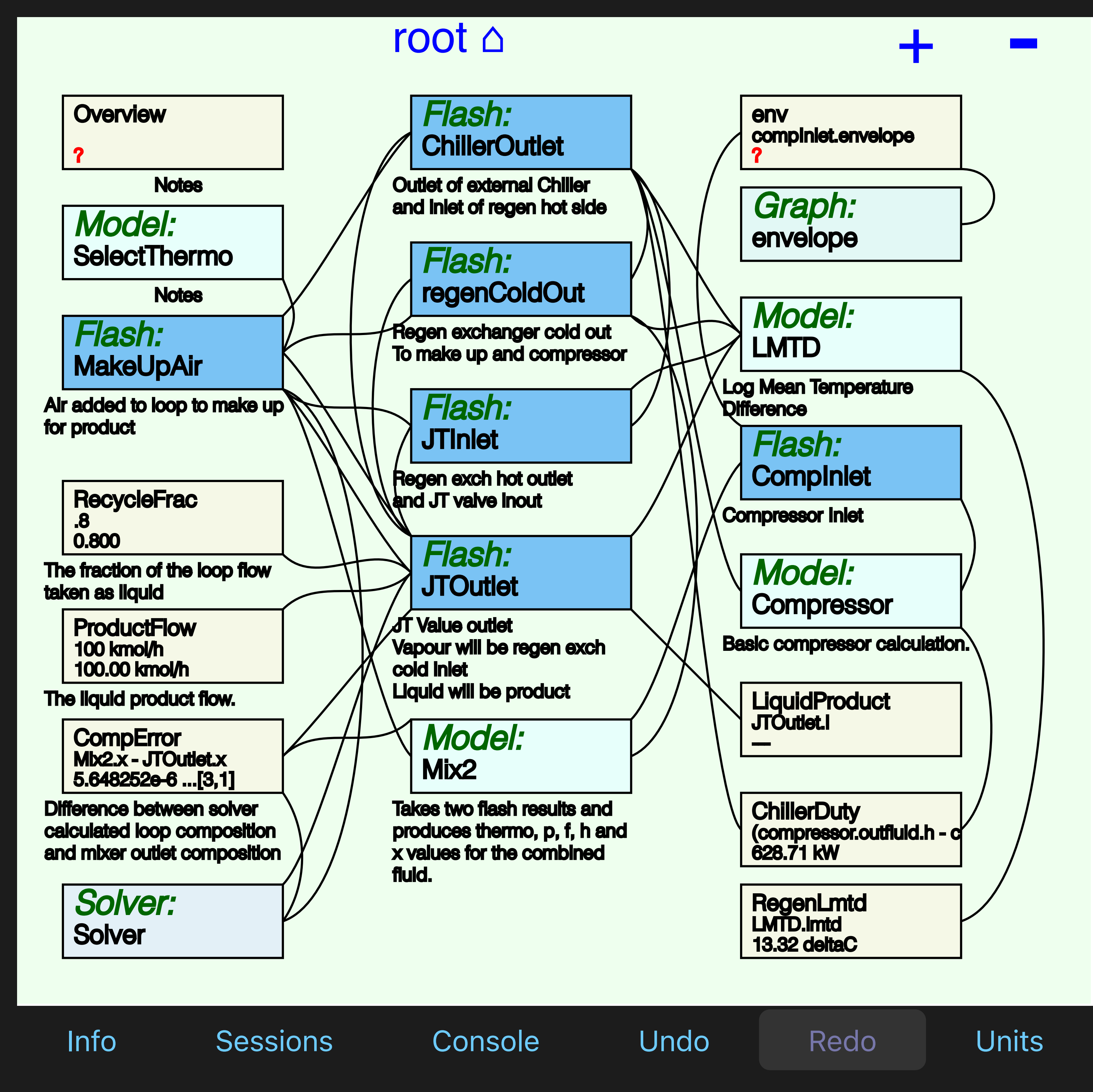
Label	Unit	B
q	Fraction	-1.00000
t	degC	3.94
p	kPa	2513.12
f	kmol/h	500.00
h	kJ/kmol	7849.21
s	kJ/kmol-K	168.08
dmolar	kmol/m^3	1.10
mwt	kg/kmol	28.76409
x	Nitrogen	0.82841
x	Oxygen	0.16319
x	Argon	8.399656e-3

LiquidProduct

Label	Unit	L
q	Fraction	0.00000
t	degC	-149.80
p	kPa	2533.12
f	kmol/h	100.00
h	kJ/kmol	-737.88
s	kJ/kmol-K	114.18
dmolar	kmol/m^3	20.47
mwt	kg/kmol	28.96985
x	Nitrogen	0.77997
x	Oxygen	0.21003
x	Argon	9.999614e-3

ChillerDuty	628.71 kW

RegenLmtd	13.32 deltaC


root ⌂
+
−
Overview
?
Notes
Model:
SelectThermo
Notes
Flash:
MakeUpAir
Air added to loop to make up for product
RecycleFrac
.8
0.800
The fraction of the loop flow taken as liquid
ProductFlow
100 kmol/h
100.00 kmol/h
The liquid product flow.
CompError
Mix2.x - JTOutlet.x
5.648252e-6 ...[3,1]
Difference between solver calculated loop composition and mixer outlet composition
Solver:
Solver
Flash:
ChillerOutlet
Outlet of external Chiller and inlet of regen hot side
Flash:
regenColdOut
Regen exchanger cold out To make up and compressor
Flash:
JTInlet
Regen exch hot outlet and JT valve inout
Flash:
JTOutlet
JT Value outlet
Vapour will be regen exch cold inlet
Liquid will be product
Model:
Mix2
Takes two flash results and produces thermo, p, f, h and x values for the combined fluid.
env
compInlet.envelope
?
Graph:
envelope
Model:
LMTD
Log Mean Temperature Difference
Flash:
CompInlet
Compressor Inlet
Model:
Compressor
Basic compressor calculation.
LiquidProduct
JTOutlet.l
—
ChillerDuty
(compressor.outfluid.h - c
628.71 kW
RegenLmtd
LMTD.lmtd
13.32 deltaC
Info
Sessions
Console
Undo
Redo
Units