REFRIGERATION CYCLES

Carnot Cycle

We start discussing the well-known Carnot cycle in its refrigeration mode.

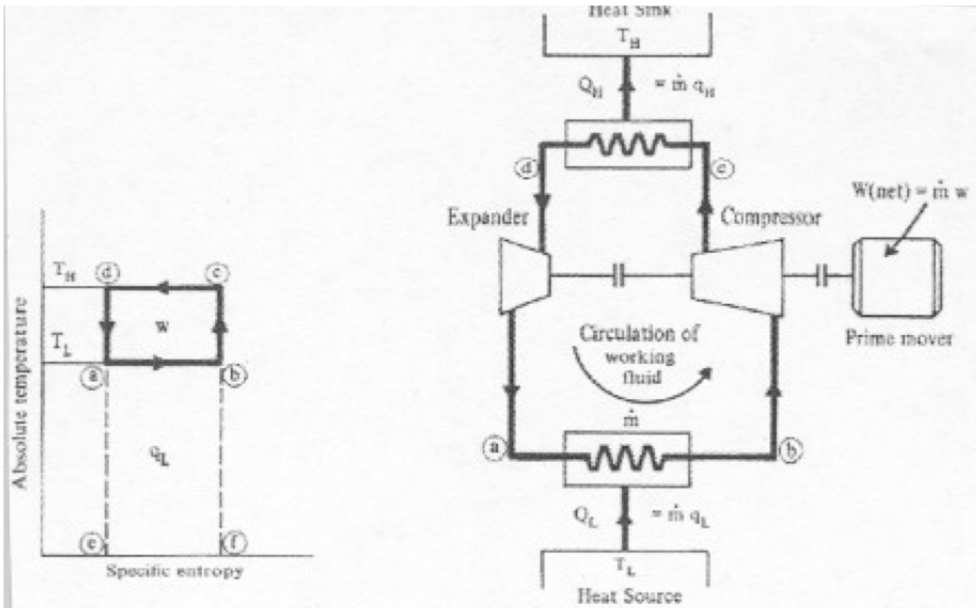

Figure 1: *Carnot Cycle*

In this cycle we define the coefficient of performance as follows:

$$COP = \frac{q_L}{w} = \frac{T_L}{T_H - T_L} \tag{1}$$

Which comes from the fact that $w = q_H - q_L$ (first law) and $q_L = T_L \Delta s$, $q_H = T_H \Delta s$ (second law). Note that *w* is also given by the area of the rectangle.

Temperature differences make the COP vary. For example, the next figure shows how COP varies with T_L (T_H is ambient in this case) and the temperature difference in exchangers.

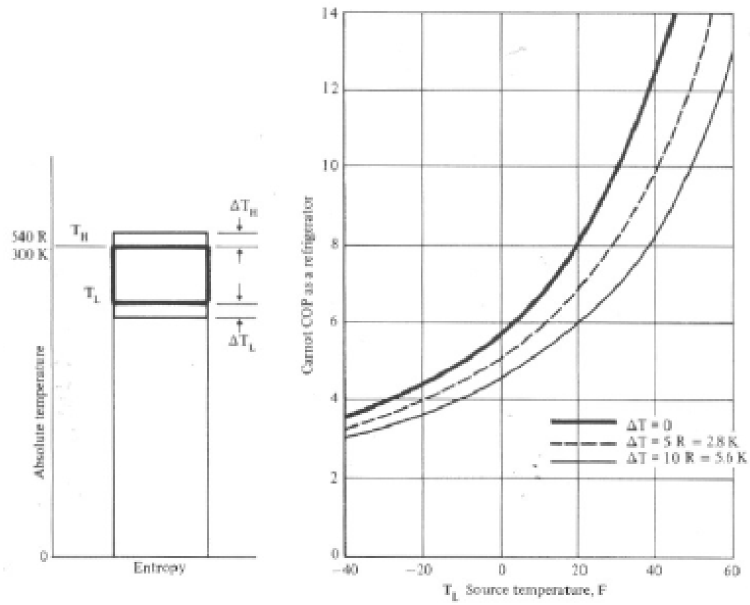

Figure 2: *COP changes with heat exchanger temperature approximation and T_L (T_H=ambient)*

We now turn our attention to a real one stage refrigeration cycle, depicted in the next figure.

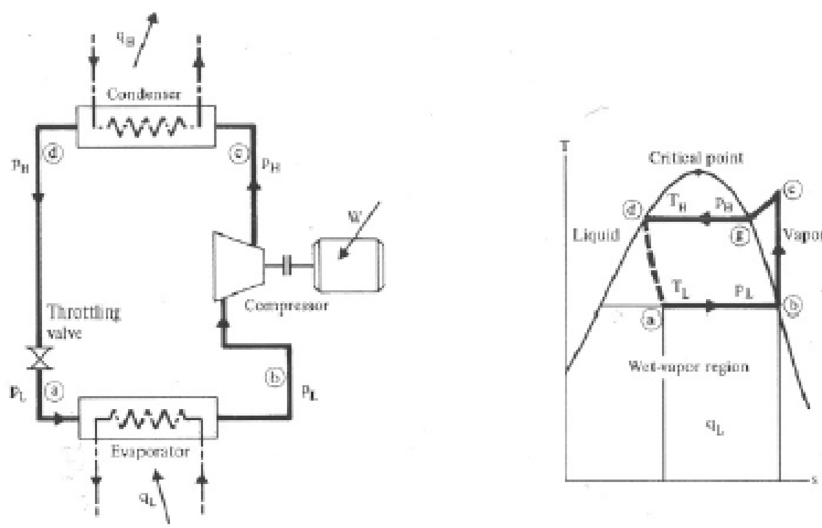

Figure 3: *Typical one-stage dry refrigeration Cycle*

We notice that:

- To be able to achieve the best match possible with the rectangular shape it is necessary to operate inside the two phase region.
- Compression is in this example performed outside the two phase region. Creating a “horn”, which is not thermodynamically advisable, is mechanically better. For this reason, this cycle is called “dry” cycle. A “wet” cycle is shown in the next figure.

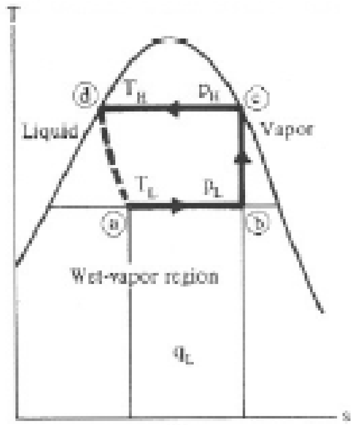

Figure 4: *Wet refrigeration Cycle*

- The expander has been substituted by a throttling valve. If an expander had been used the line from **d** to **a** would be a vertical line. This is also done for mechanical reasons.

The refrigeration cycles can also be represented in a P-H diagram.

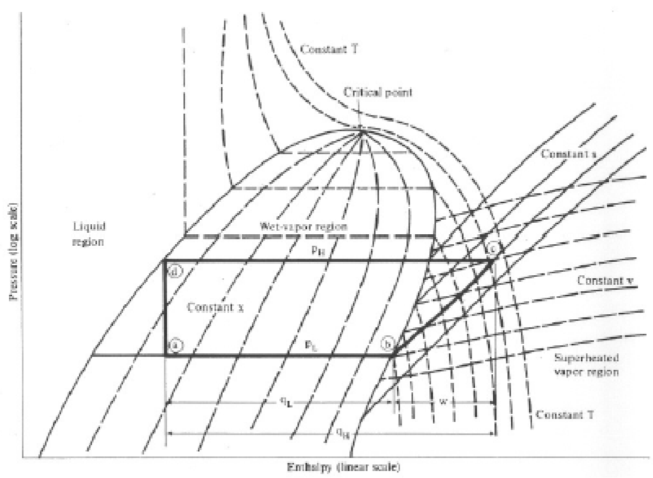

Figure 5: *P-H diagram representation of a dry refrigeration cycle*

Refrigerant fluid choice: We now turn our attention to the fluids. Usually, one tends to pick p_L as low as possible, but not below atmospheric pressure. Thus, the refrigerant chosen needs to have a normal boiling point compatible with the lowest temperature of the cycle (usually 10^oC lower than the system one wants to cool). The higher pressure needs to be compatible with the cooling media used for q_H. If this is cooling water, then the T_H needs to be around 10^oC higher than the available cooling water temperature. The next table shows the existing refrigerants. It is followed by the boiling temperature and rang of selected refrigerants.

Table 2-1: Refrigerants

ASHRAE STANDARD DESIGNATION OF REFRIGERANTS

Refrigerant number	Chemical name	Chemical formula
218	Octafluoropropane	$CF_3CF_2CF_3$
290*	Propane	$CH_3CH_2CH_3$
Cyclic organic compounds		
C316	Dichlorohexafluorocyclobutane	$C_4Cl_2F_6$
C317	Monochloroheptafluorocyclobutane	C_4ClF_7
C318	Octafluorocyclobutane	C_4F_8
Azeotropes		
500	Refrigerants 12/152a 73.8/26.2wt %‡	CCl_2F_2/CH_3CHF_2
501	Refrigerants 22/12 75/25wt %	$CHClF_2/CCl_2F_2$
502	Refrigerants 22/115 48.8/51.2wt %	$CHClF_2/CClF_2CF_3$
Miscellaneous organic compounds		
Hydrocarbons		
50	Methane	CH_4
170	Ethane	CH_3CH_3
290	Propane	$CH_3CH_2CH_3$
600	Butane	$CH_3CH_2CH_2CH_3$
601	Isobutane	$CH(CH_3)_3$
1150†	Ethylene	$CH_2{=}CH_2$
1270†	Propylene	$CH_3CH{=}CH_2$
Oxygen compounds		
610	Ethyl ether	$C_2H_5OC_2H_5$
611	Methyl formate	$HCOOCH_3$
Nitrogen compounds		
630	Methyl amine	CH_3NH_2
631	Ethyl amine	$C_2H_5NH_2$
Inorganic compounds (Cryogenic)		
702	Hydrogen (normal and *para*)	H_2
704	Helium	He
720	Neon	Ne
728	Nitrogen	N
729	Air	$0.21O_2, 0.78N_2, 0.01A$
732	Oxygen	O_2
740	Argon	A

* Methane, ethane, and propane appear in the halocarbon section in their proper numerical order, but these compounds are not halocarbons.

† Ethylene and propylene appear in the hydrocarbon section to indicate that these compounds are hydrocarbons, but are properly identified in the section unsaturated organic compounds.

‡ Carrier Corporation Document 2-D-127, p. 1.

Table 2-1: Refrigerants Continued)

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Table 2-1: Refrigerants Continued)

ASHRAE STANDARD DESIGNATION OF REFRIGERANTS

Refrigerant number	Chemical name	Chemical formula
Inorganic compounds (noncryogenic)		
717	Ammonia	NH_3
718	Water	H_2O
744	Carbon dioxide	CO_2
744A	Nitrous oxide	N_2O
764	Sulfur dioxide	SO_2
Unsaturated organic compounds		
1112a	Dichlorodifluoroethylene	$CCl_2{=}CF_2$
1113	Monochlorotrifluoroethylene	$CClF{=}CF_2$
1114	Tetrafluoroethylene	$CF_2{=}CF_2$
1120	Trichloroethylene	$CHCl{=}CCl_2$
1130	Dichloroethylene	$CHCl{=}CHCl$
1132a	Vinylidene fluoride	$CH_2{=}CF_2$
1140	Vinyl chloride	$CH_2{=}CHCl$
1141	Vinyl fluoride	$CH_2{=}CHF$
1150	Ethylene	$CH_2{=}CH_2$
1270	Propylene	$CH_3CH{=}CH_2$

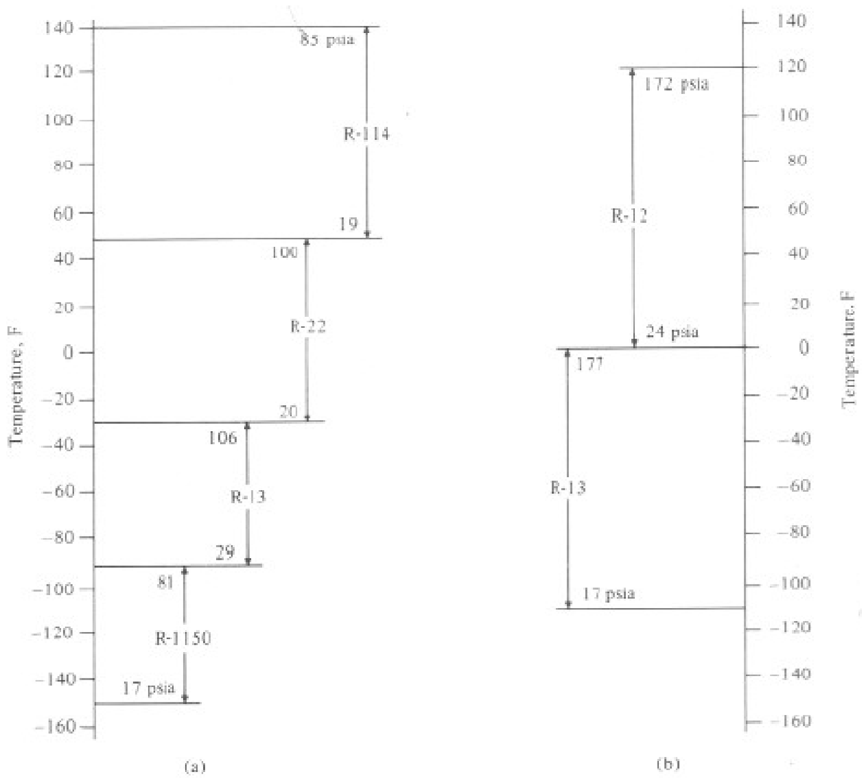
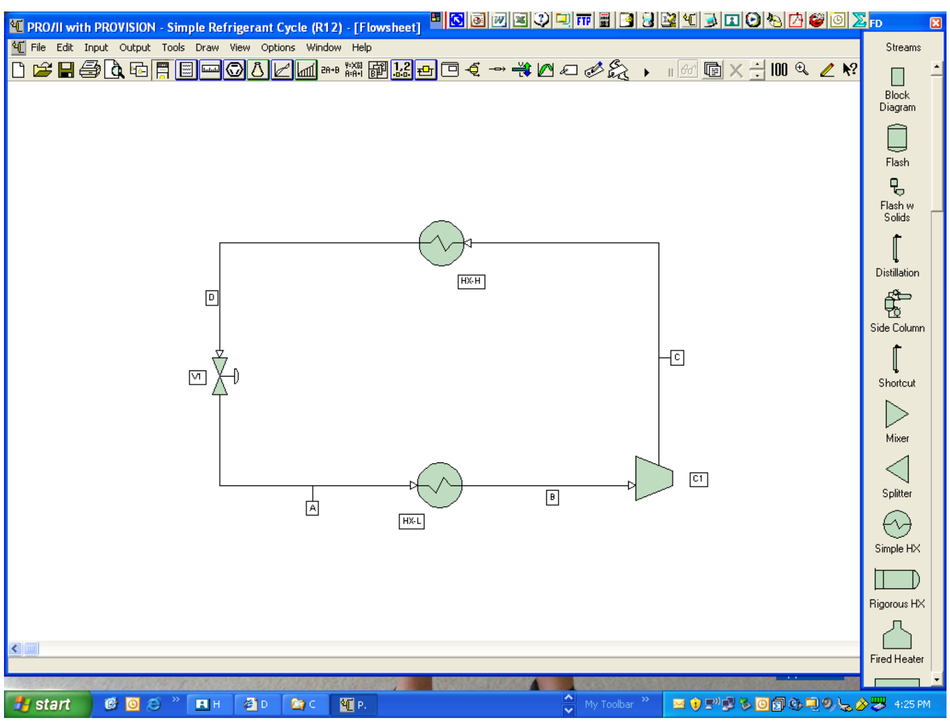


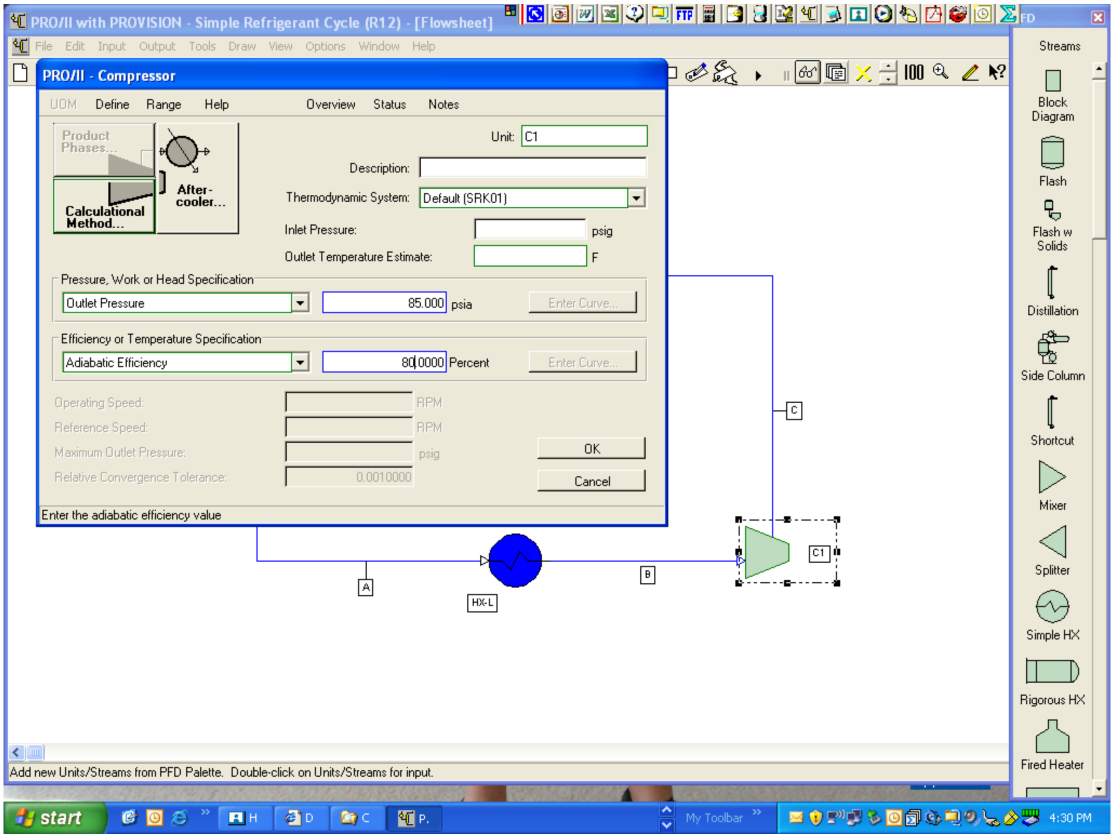
Figure 2-6: *Temperature Ranges of Refrigerants*

We now turn to Pro II to show how a refrigerant cycle is built.
We start with entering the cycle as follows:

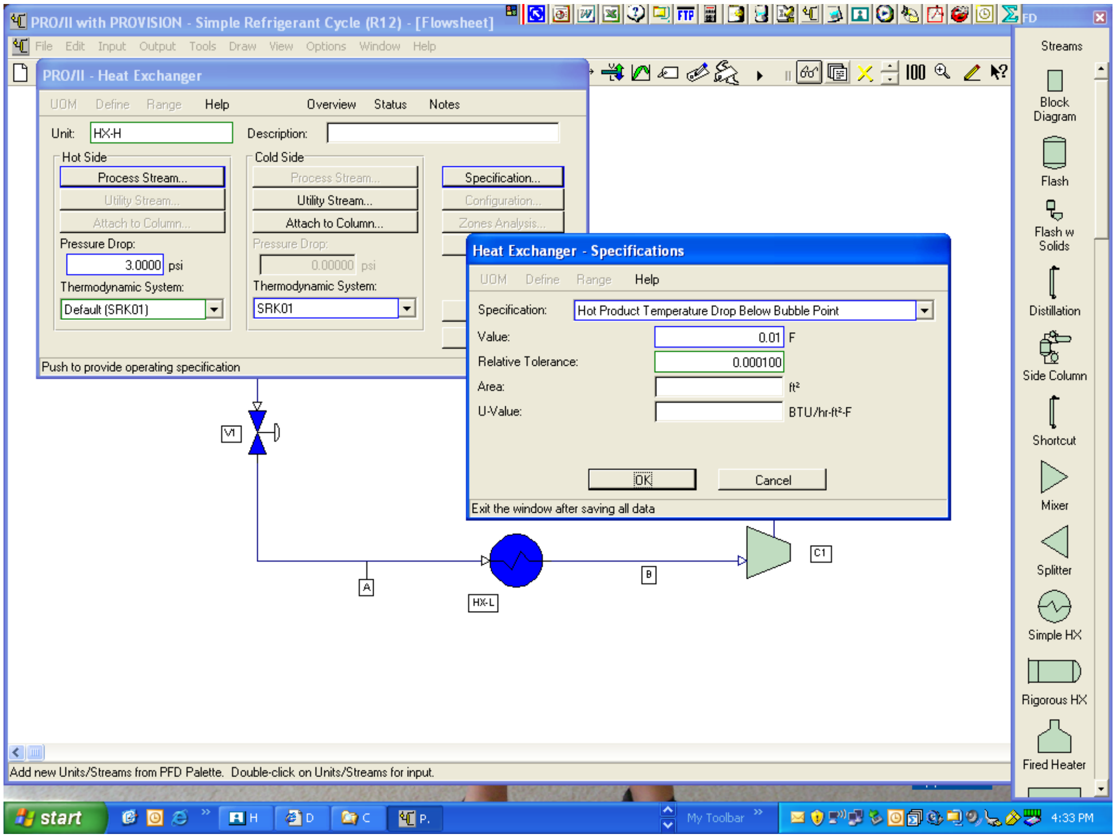


We pick R12, which will allow us to cool down anything to

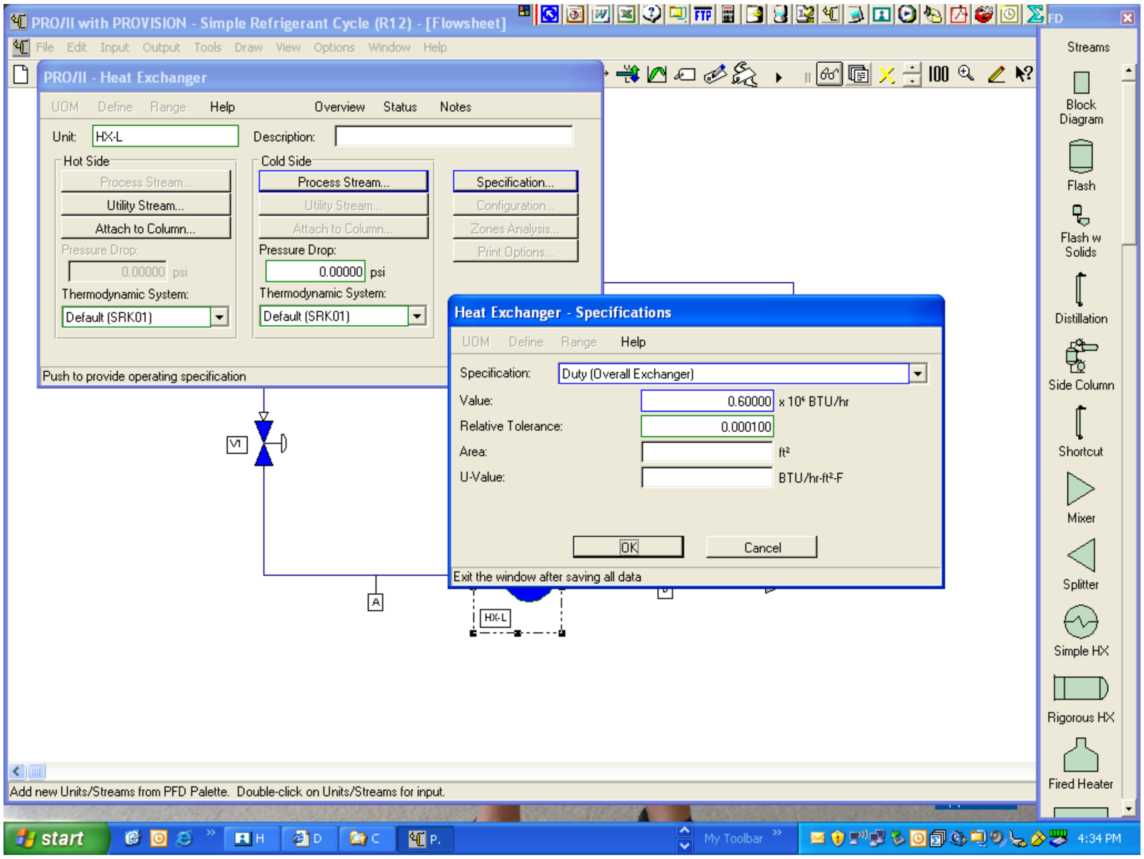
Next we define the outlet pressure of the compressor. This needs to be such that stream C (after the cooler) is higher than 60 ^{o}F. To start we choose around 85 psia.



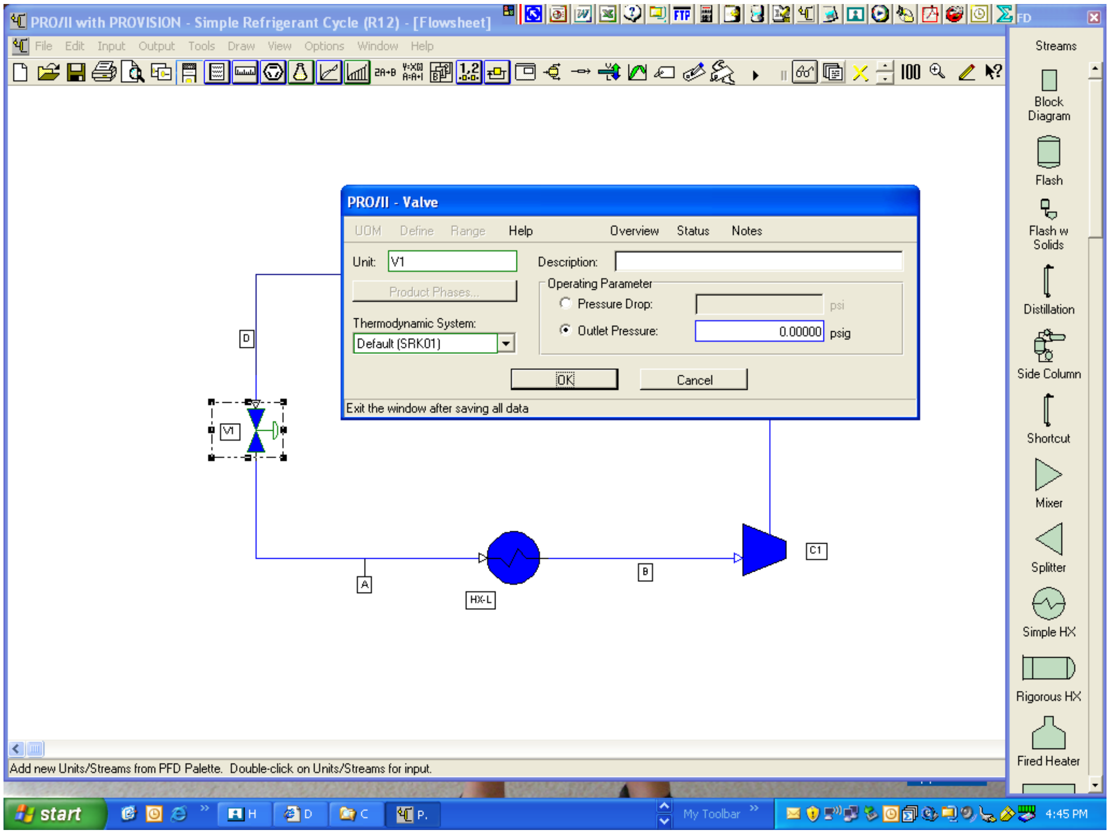
Next we define the top heat exchanger, by specifying an outlet temperature slightly below the bubble point.



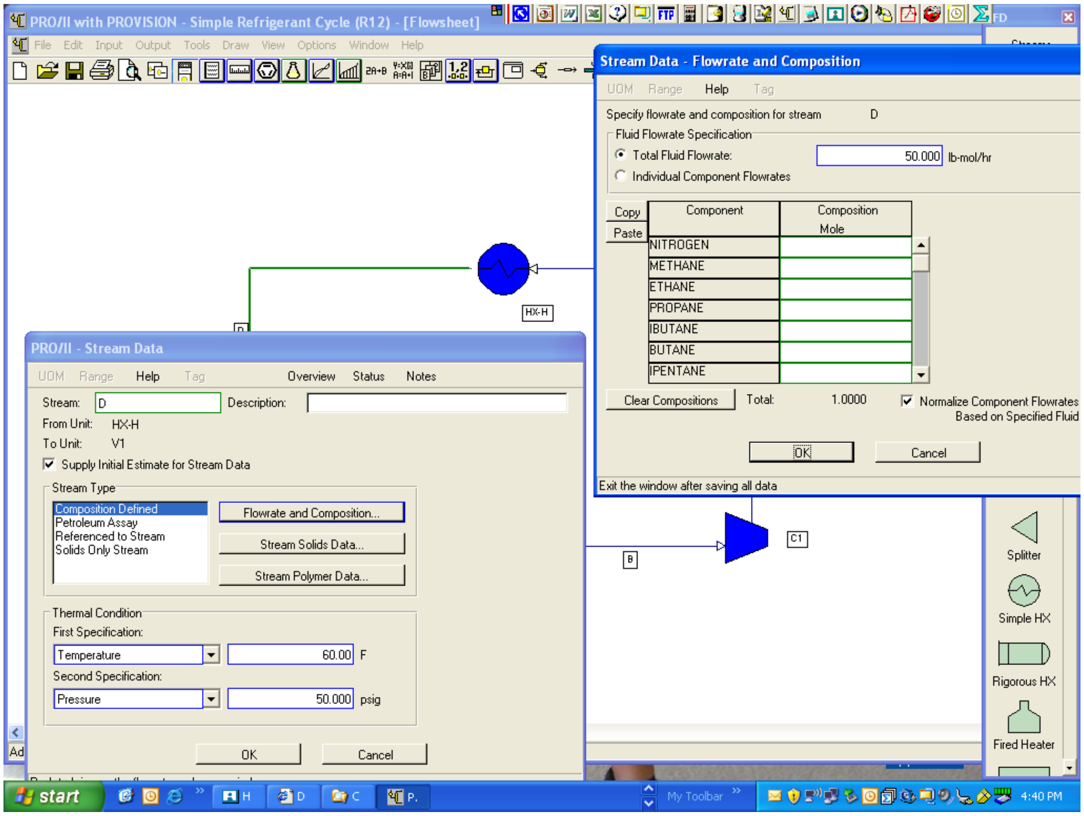
We continue by specifying the duty of the bottom exchanger. This is customary because this is the targeted design goal of the cycle.



We enter the outlet pressure of the valve (atmospheric).

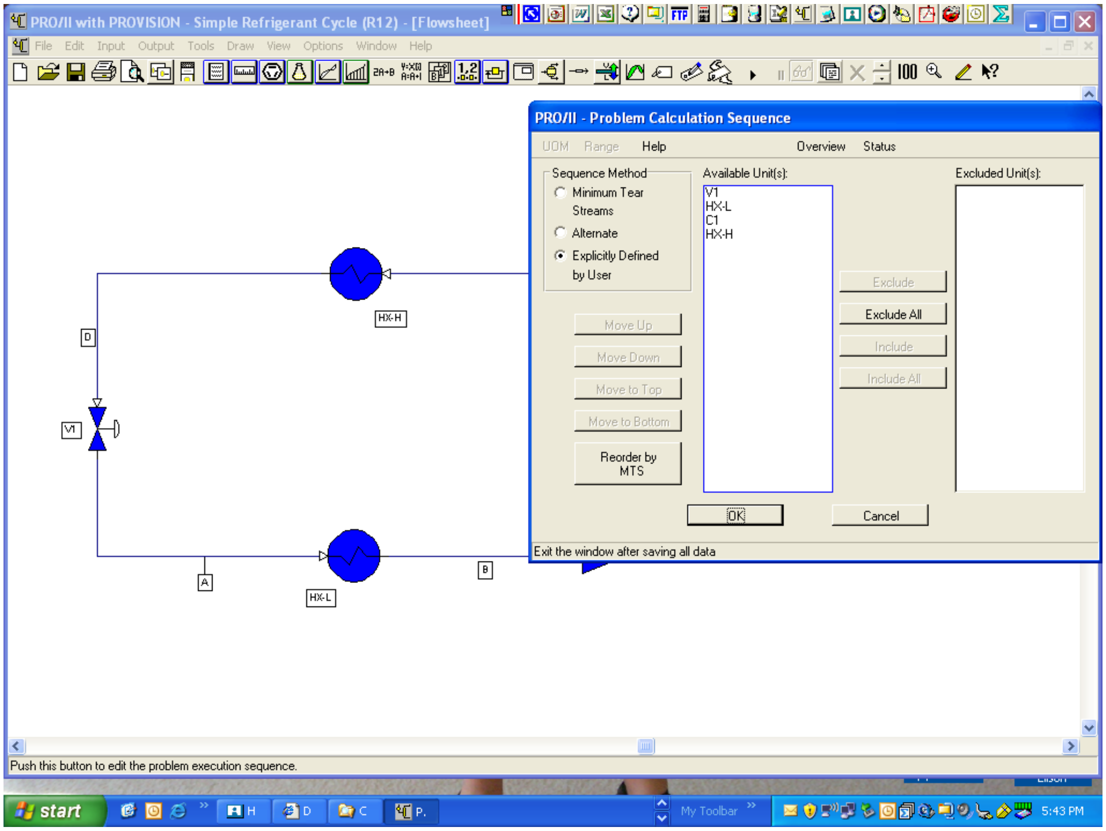


We also realize that this flowsheet does not have input or output streams. Thus, to start the simulation, one needs to give an initial value to a stream. We chose stream D, and initialize with a flowrate that is guessed.



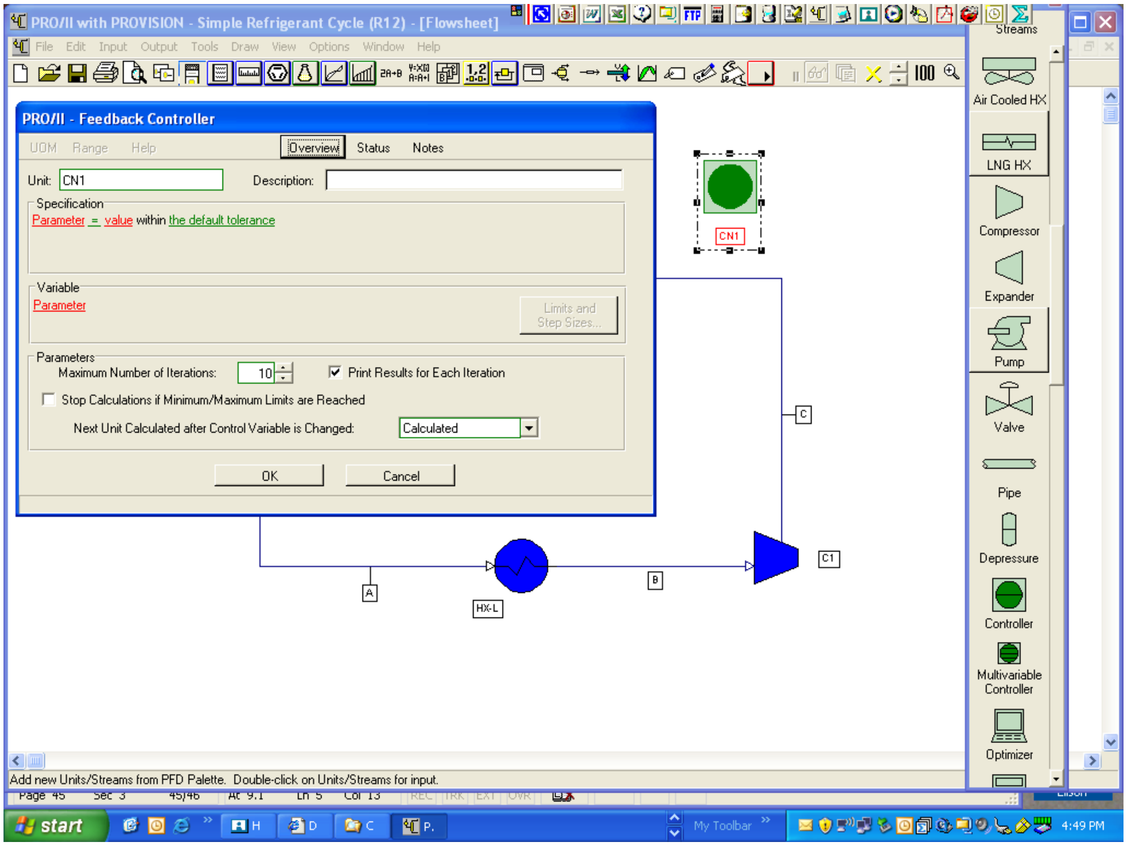
If the flowrate chosen is too high, then the inlet of the compressor will be two phase and this is not advisable. If the flowrate is too low, the cycle will loose efficiency (the "horn" will get larger).

Warning: Pro II may not realize internally that it needs to solve the unit that the initialized stream feeds to and try to continue until it reaches convergence in the loop but it will loose the input data. To avoid problems we specify the order in which we want the flowsheet to solve by clicking in the unit sequence button.

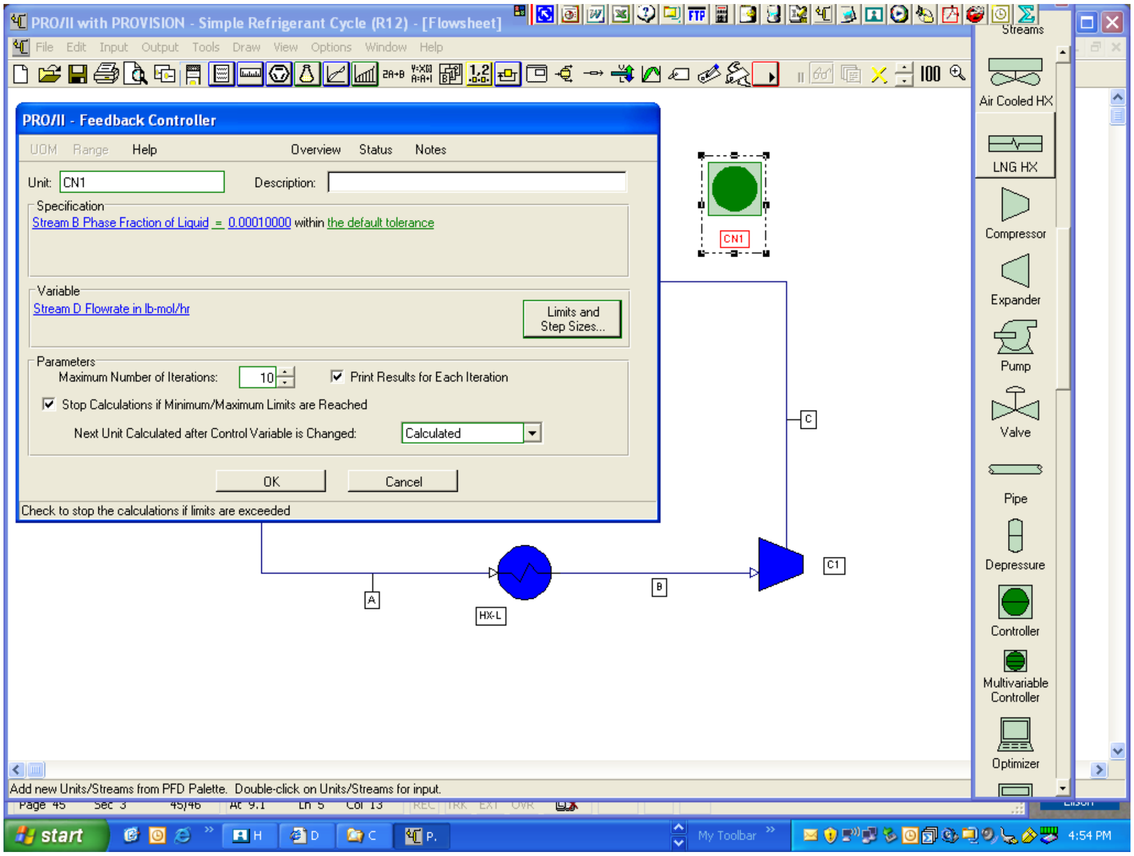


Construct the simulation above described and determine the right flowrate in the cycle. Determine all temperatures and obtain the COP. Compare it with a Carnot Cycle.

The above exercise can be done automatically using a “controller”, which is a type of “spec and vary” equivalent to “Goal Seek” in Excel. Once the controller is picked, double clicking on it reveals the menu.



Thus, we choose to have the inlet to the compressor just slightly above dew point (specification) and we vary the flowrate, just as we did by hand. It is, however, easier to specify a very low liquid fraction. Make sure the starting point is close to the right value. Sometimes the controller has a hard time converging.


PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]
File Edit Input Output Tools Draw View Options Window Help
PRO/II - Feedback Controller
UOM Range Help Overview Status Notes
Unit: CN1
Description:
Specification
Stream B Phase Fraction of Liquid = 0.00010000 within the default tolerance
Variable
Stream D Flowrate in lb-mol/hr
Limits and Step Sizes...
Parameters
Maximum Number of Iterations: 10
Print Results for Each Iteration
Stop Calculations if Minimum/Maximum Limits are Reached
Next Unit Calculated after Control Variable is Changed: Calculated
OK
Cancel
Check to stop the calculations if limits are exceeded
CN1
C
C1
A
B
HX-L
Streams
Air Cooled HX
LNG HX
Compressor
Expander
Pump
Valve
Pipe
Depressure
Controller
Multivariable Controller
Optimizer
Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.
start
My Toolbar
4:54 PM