REFRIGERATION CYCLES

Carnot Cycle

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

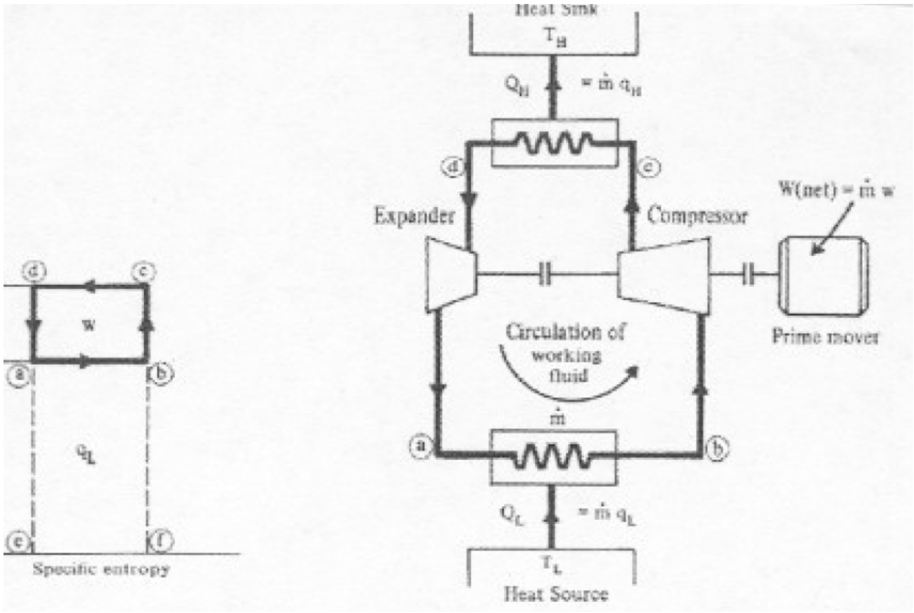


Figure 1: *Carnot Cycle*

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

$$COP = \frac{q_L}{w} = \frac{T_L}{T_H - T_L} \qquad (1)$$

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.

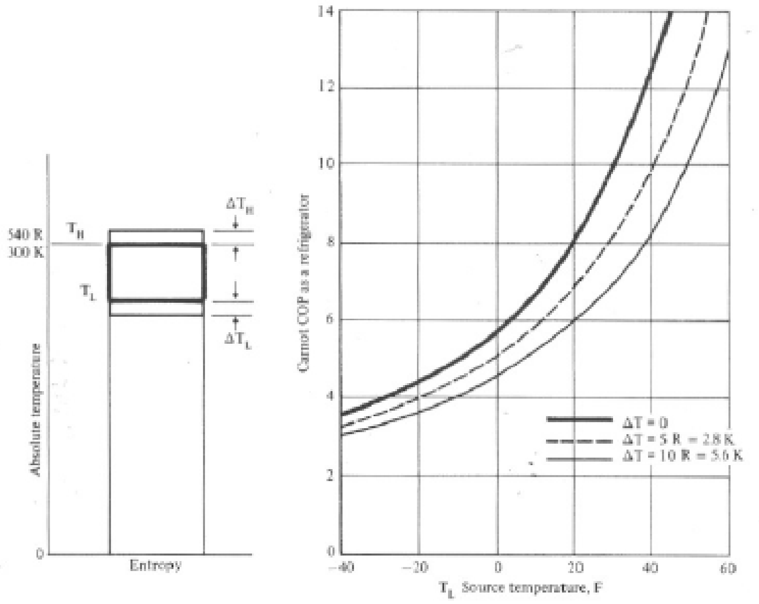


Figure 2: *COP changes with heat exchanger temperature approximation and T_L (T_H=ambient)*

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

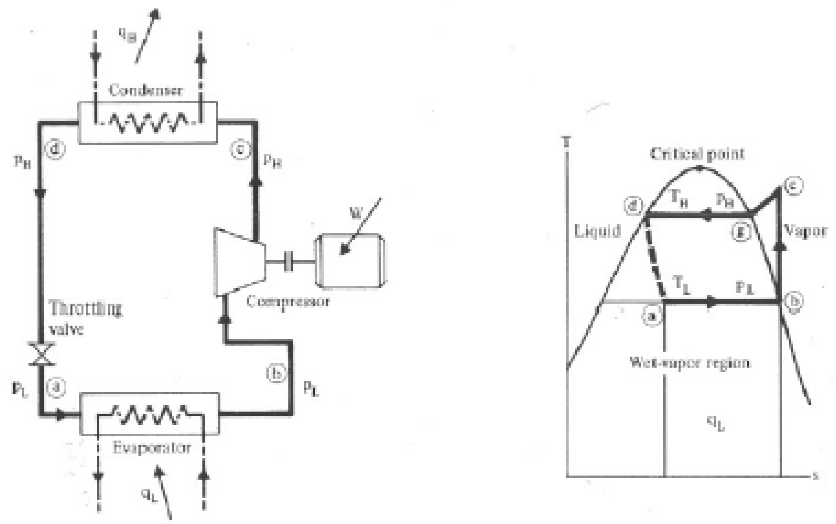


Figure 3: *Typical one-stage dry refrigeration Cycle*

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.

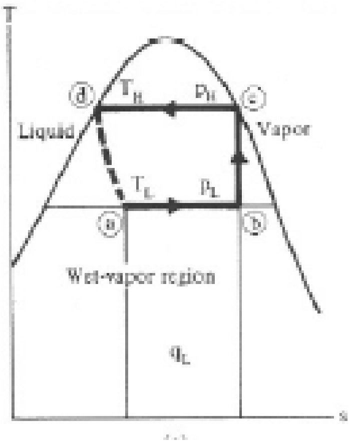


Figure 4: *Wet refrigeration Cycle*

- 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.

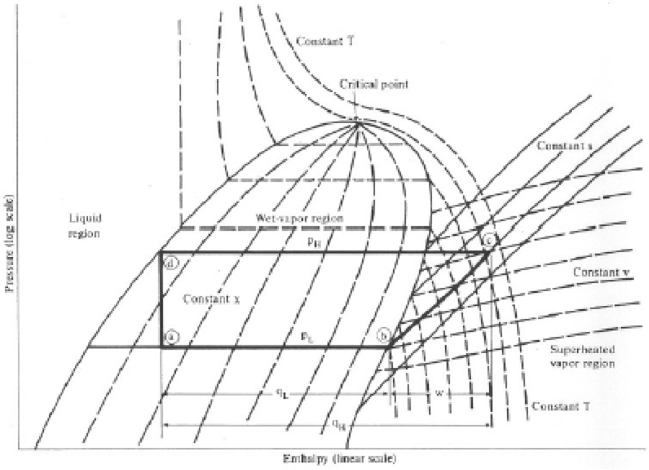
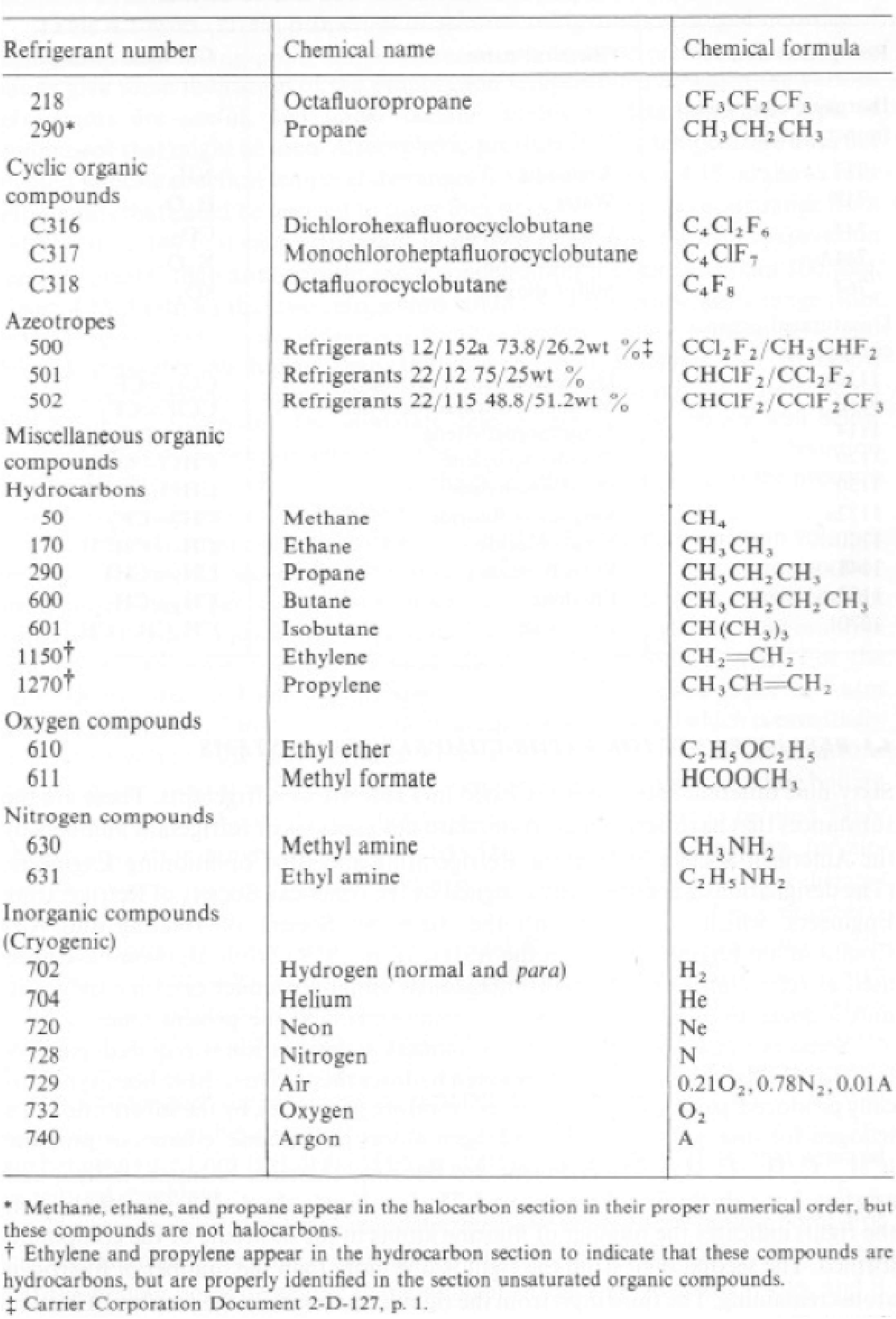


Figure 5: *P-H diagram representation of a dry refrigeration cycle*

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°C 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°C 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 1: Refrigerants



ASHRAE STANDARD DESIGNATION OF REFRIGERANTS

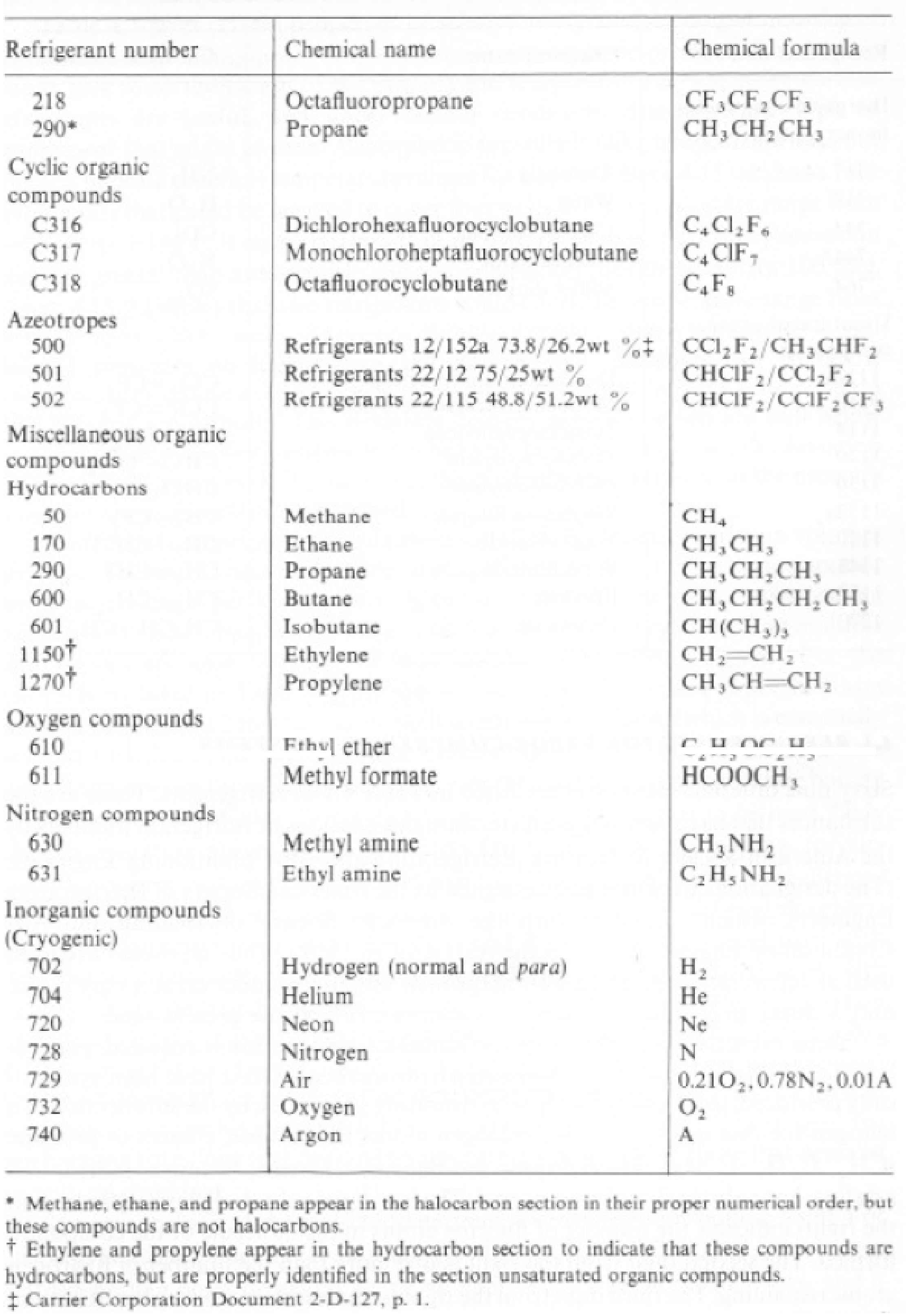
Refrigerant number	Chemical name	Chemical formula
218	Octafluoropropane	$CF_3CF_2CF_3$
290*	Propane	$CH_3CH_2CH_3$
Cyclic organic compounds		
C316	Dichlorohexafluorocyclobutane	$C_4Cl_2F_6$
C317	Monochloroheptafluorocyclobutane	C_4ClF_7
C318	Octafluorocyclobutane	C_4F_8
Azeotropes		
500	Refrigerants 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 1: Refrigerants Continued)



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C318	Octafluorocyclobutane	C_4F_8
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Oxygen compounds		
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611	Methyl formate	$HCOOCH_3$
Nitrogen compounds		
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Inorganic compounds (Cryogenic)		
702	Hydrogen (normal and *para*)	H_2
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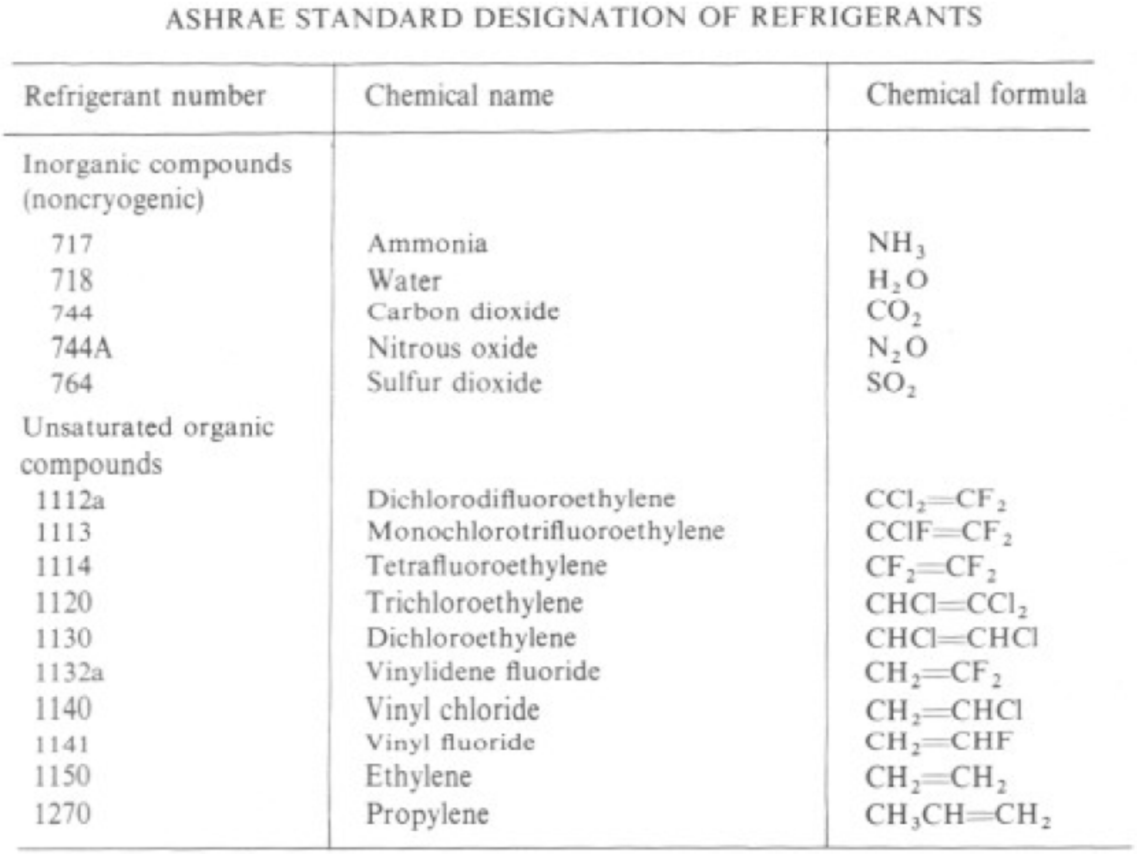


ASHRAE STANDARD DESIGNATION OF REFRIGERANTS

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	$CH_3CH{=}CH_2$

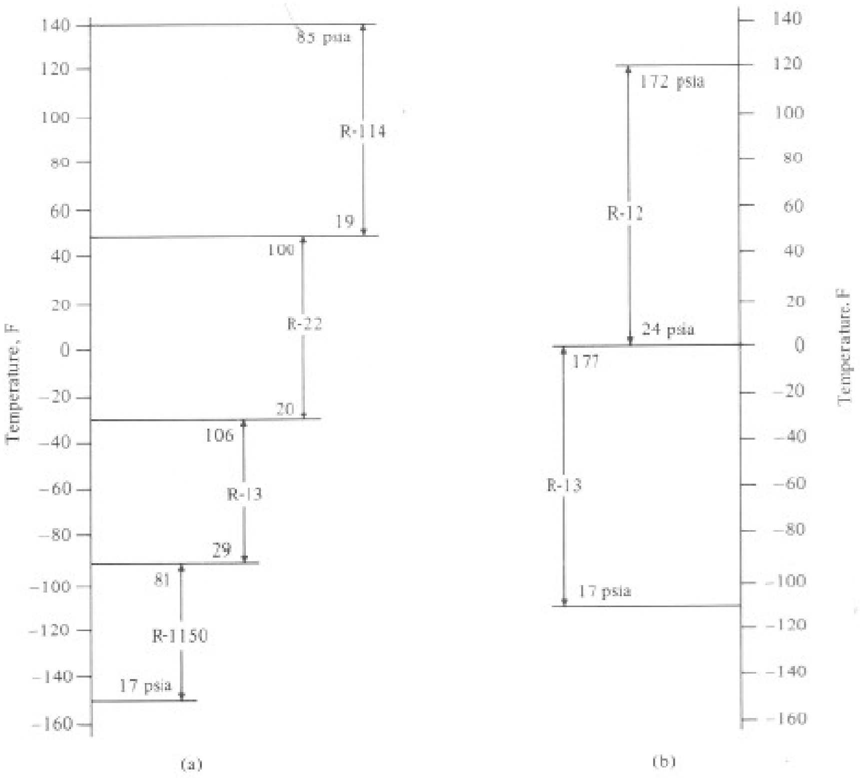
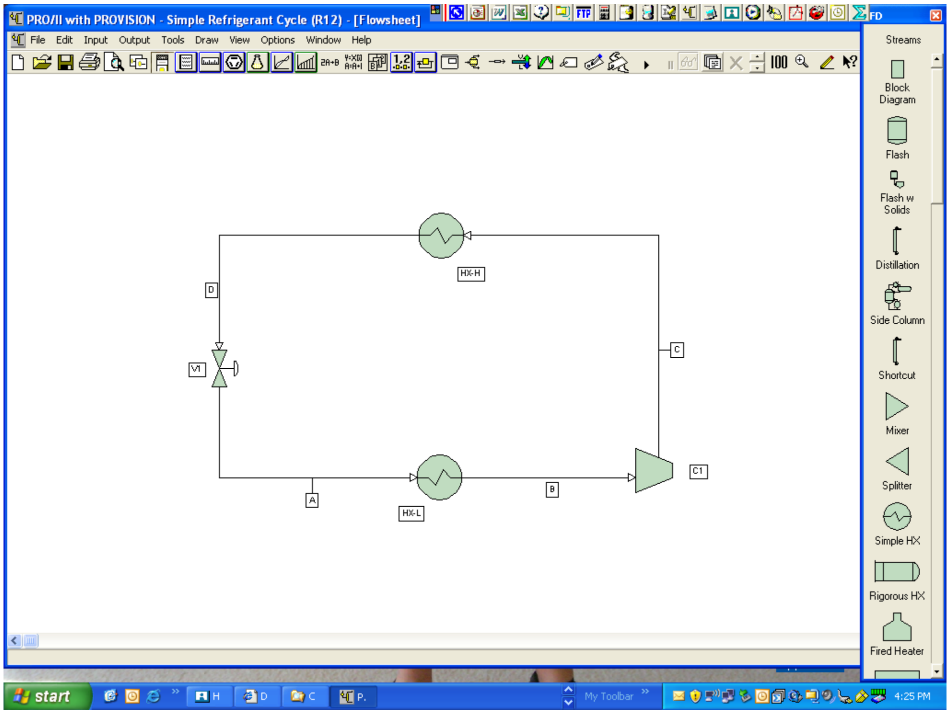


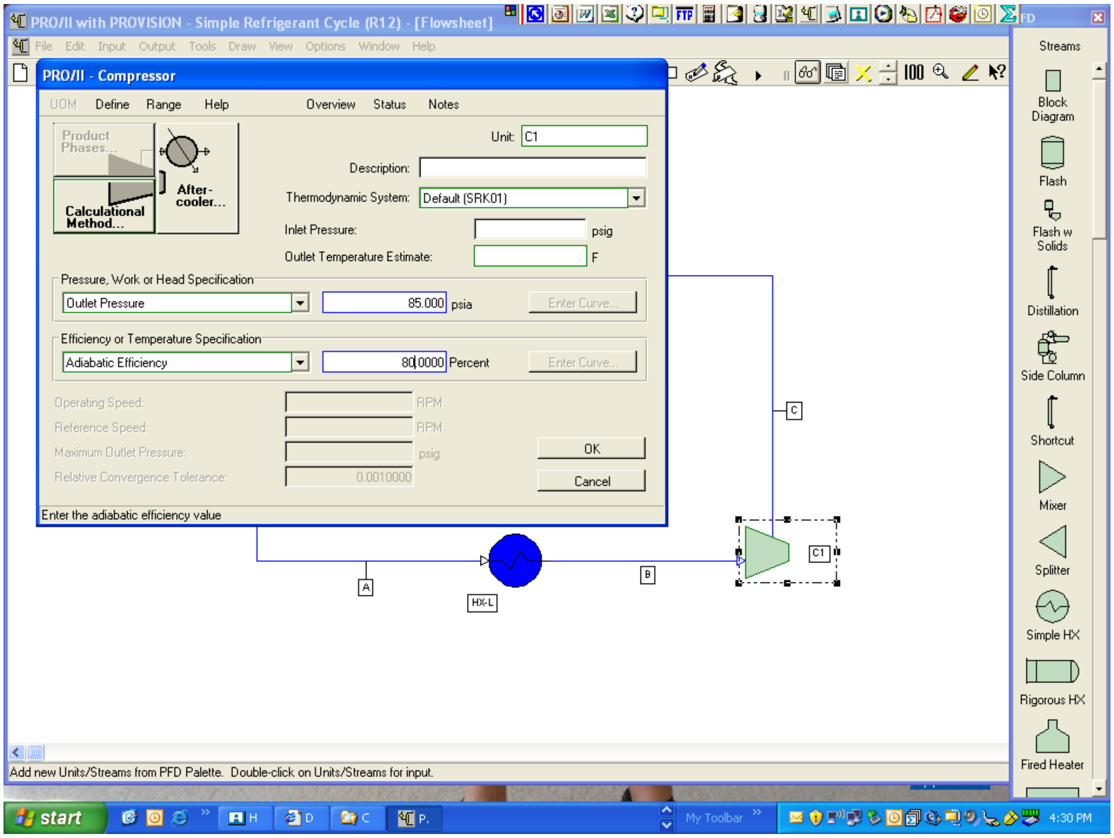
Figure 6: *Temperature Ranges of Refrigerants*

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.


PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]

PRO/II - Compressor

Unit: C1

Description:

Thermodynamic System: Default (SRK01)

Inlet Pressure: psig

Outlet Temperature Estimate: F

Pressure, Work or Head Specification: Outlet Pressure 85.000 psia

Efficiency or Temperature Specification: Adiabatic Efficiency 80.0000 Percent

Operating Speed: RPM

Reference Speed: RPM

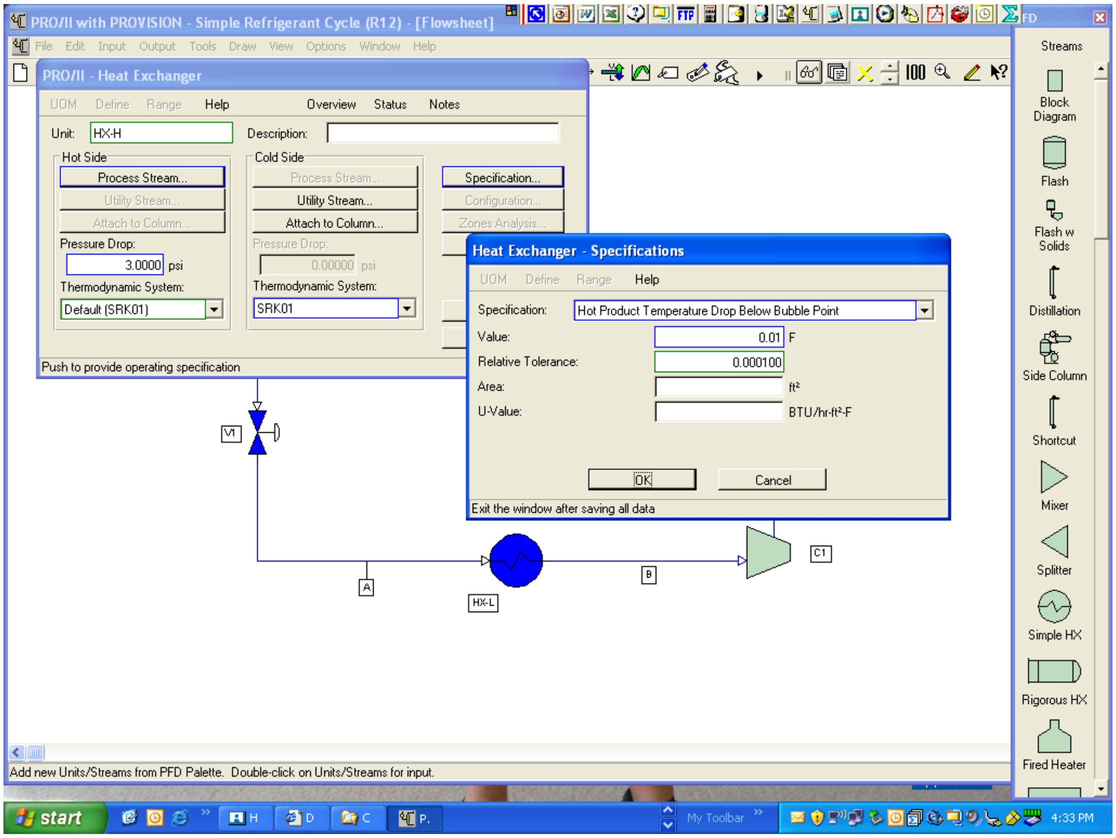
Maximum Outlet Pressure: psig

Relative Convergence Tolerance: 0.0010000

Enter the adiabatic efficiency value

Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.

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



PRO/II - Heat Exchanger

Unit: HX-H

Description:

Hot Side Pressure Drop: 3.0000 psi

Hot Side Thermodynamic System: Default (SRK01)

Cold Side Pressure Drop: 0.00000 psi

Cold Side Thermodynamic System: SRK01

Push to provide operating specification

Heat Exchanger - Specifications

Specification: Hot Product Temperature Drop Below Bubble Point

Value: 0.01 F

Relative Tolerance: 0.000100

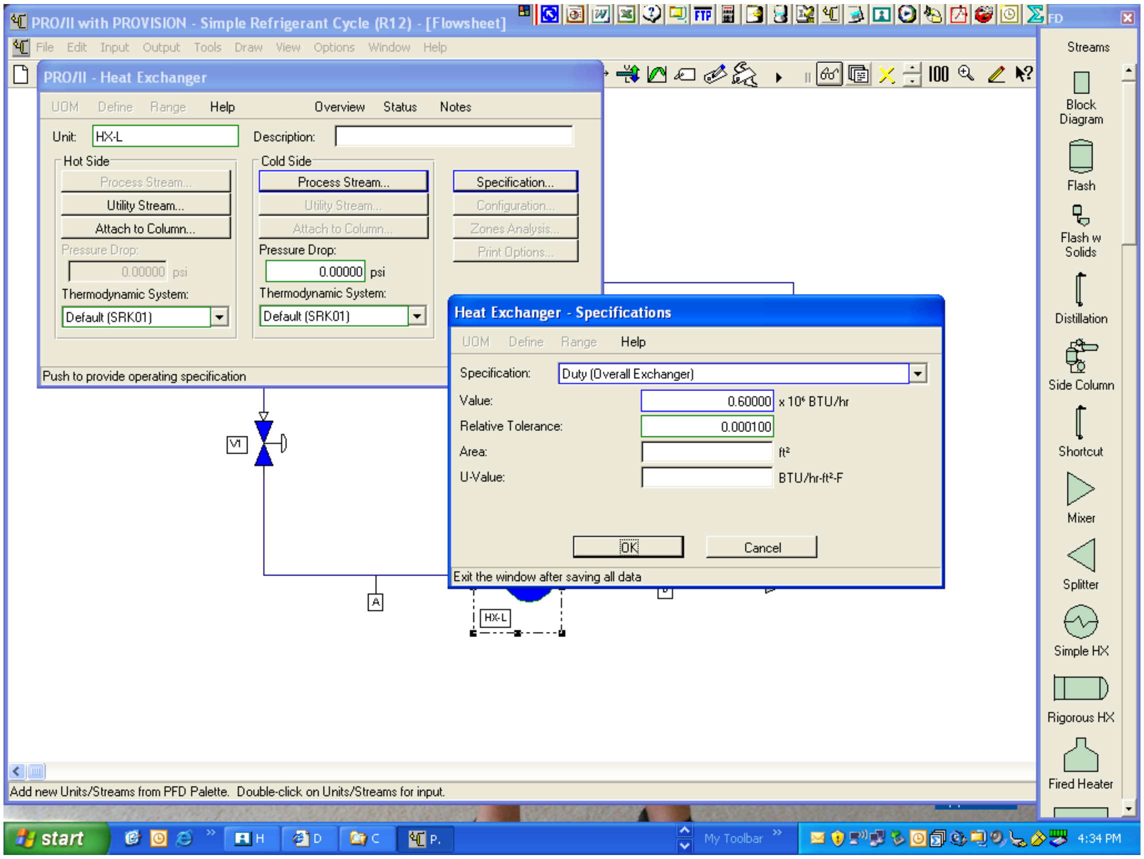
Area: ft²

U-Value: BTU/hr-ft²-F

Exit the window after saving all data

Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.

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



PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]

PRO/II - Heat Exchanger

Unit: HX-L

Description:

Hot Side

Pressure Drop: 0.00000 psi

Thermodynamic System: Default (SRK01)

Cold Side

Pressure Drop: 0.00000 psi

Thermodynamic System: Default (SRK01)

Push to provide operating specification

Heat Exchanger - Specifications

Specification: Duty (Overall Exchanger)

Value: 0.60000 x 10⁶ BTU/hr

Relative Tolerance: 0.000100

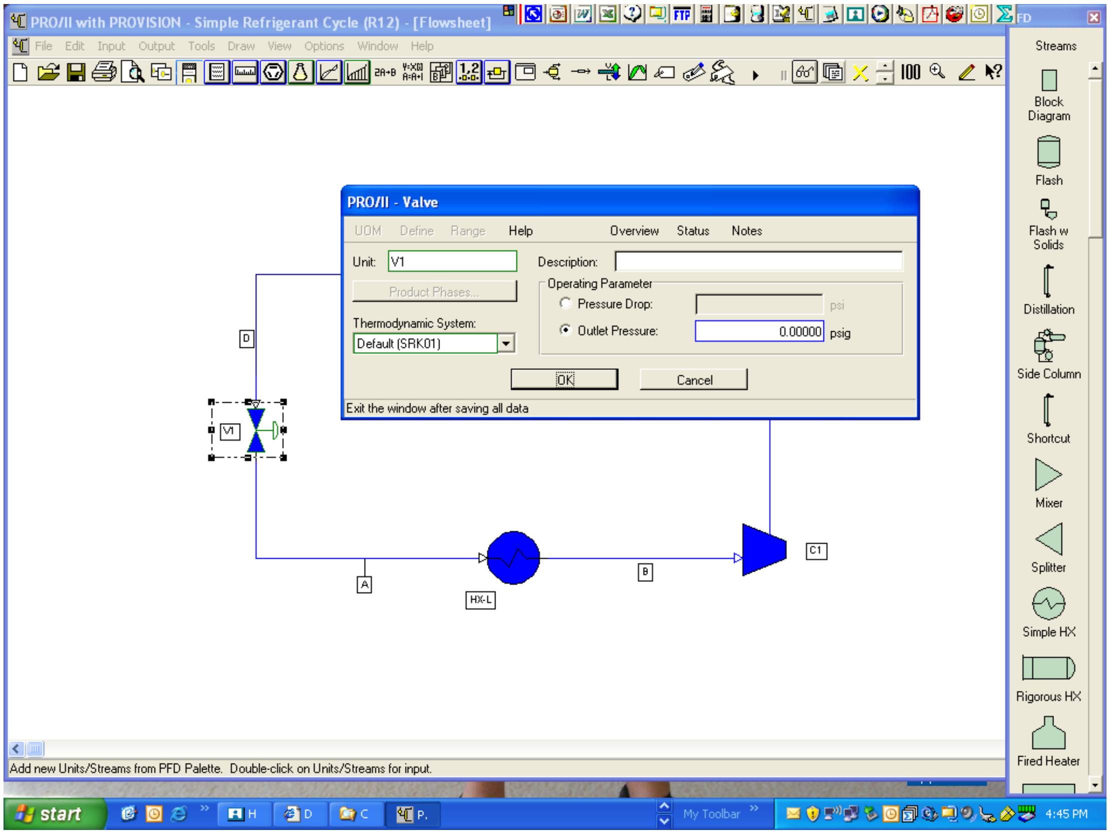
Area: ft²

U-Value: BTU/hr-ft²-F

Exit the window after saving all data

Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.

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



PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]

PRO/II - Valve

Unit: V1

Description:

Thermodynamic System: Default (SRK01)

Operating Parameter

○ Pressure Drop: psi

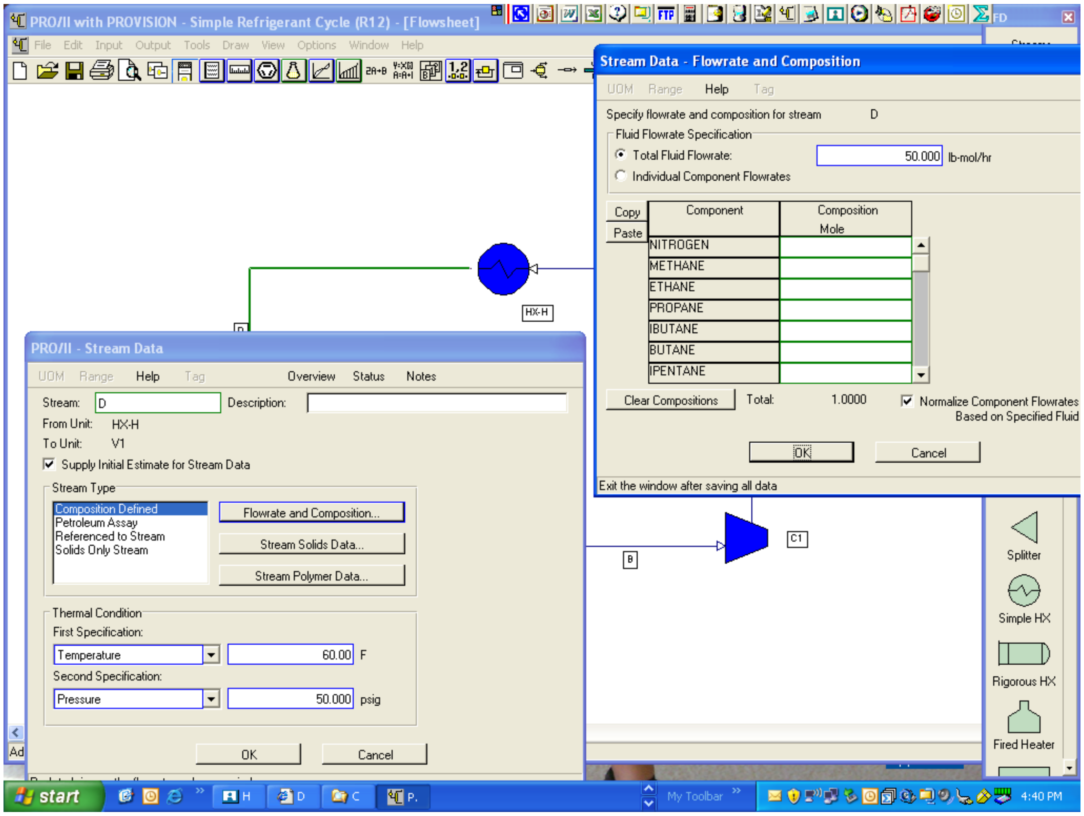
● Outlet Pressure: 0.00000 psig

OK Cancel

Exit the window after saving all data

Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.

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.



PRO/II - Stream Data

Stream: D Description:
From Unit: HX-H
To Unit: V1
☑ Supply Initial Estimate for Stream Data

Stream Type: Composition Defined (selected); Petroleum Assay; Referenced to Stream; Solids Only Stream

Thermal Condition
First Specification: Temperature 60.00 F
Second Specification: Pressure 50.000 psig

Stream Data - Flowrate and Composition

Specify flowrate and composition for stream D

Fluid Flowrate Specification
● Total Fluid Flowrate: 50.000 lb-mol/hr
○ Individual Component Flowrates

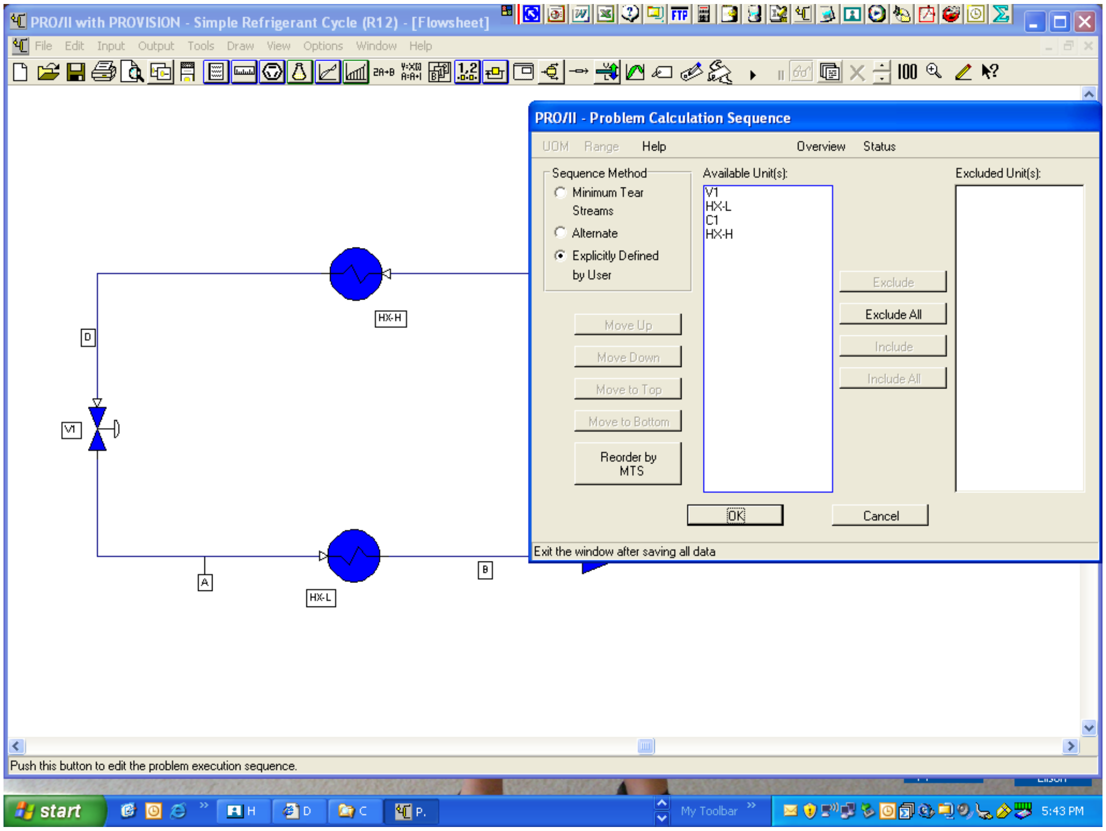
Component	Composition Mole
NITROGEN	
METHANE	
ETHANE	
PROPANE	
IBUTANE	
BUTANE	
IPENTANE	

Total: 1.0000
☑ Normalize Component Flowrates Based on Specified Fluid

Exit the window after saving all data

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.



PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]

PRO/II - Problem Calculation Sequence

Sequence Method
○ Minimum Tear Streams
○ Alternate
● Explicitly Defined by User

Available Unit(s):
V1
HX-L
C1
HX-H

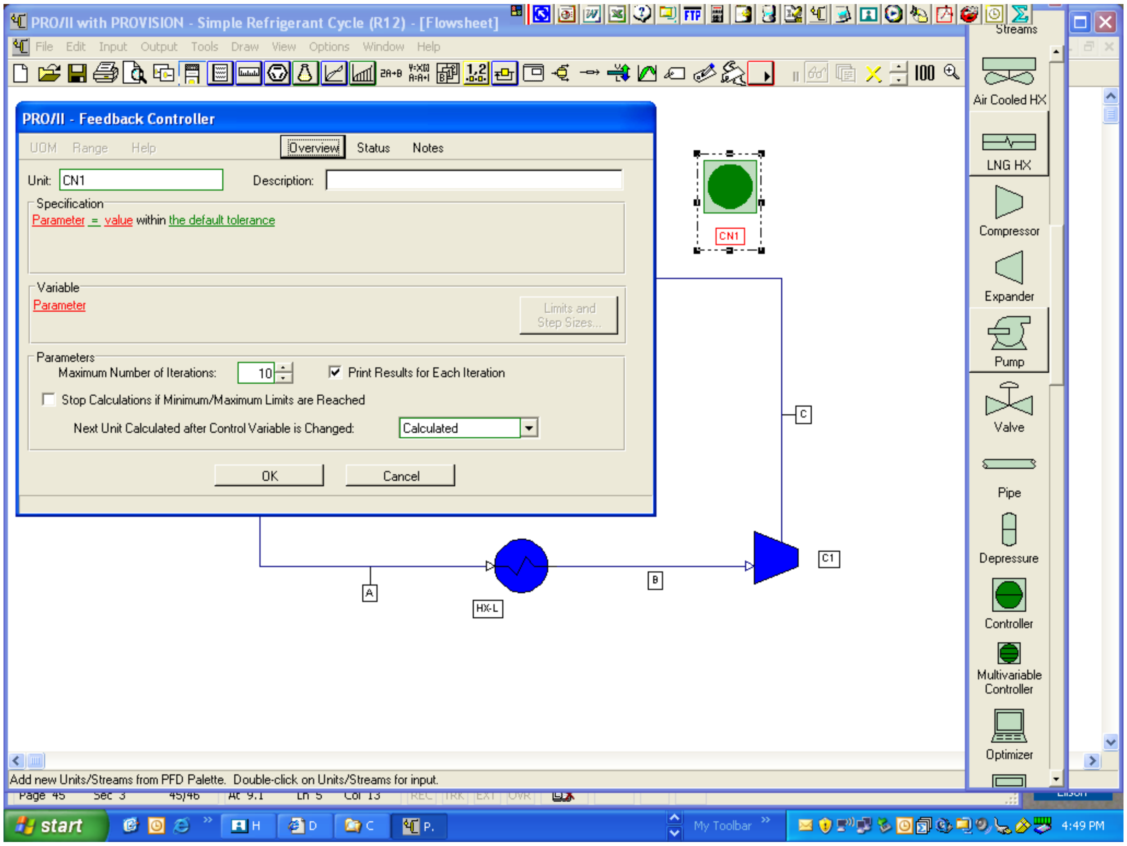
Excluded Unit(s):

Exit the window after saving all data

Push this button to edit the problem execution sequence.

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.



PRO/II with PROVISION - Simple Refrigerant Cycle (R12) - [Flowsheet]

PRO/II - Feedback Controller

Unit: CN1

Description:

Specification

Parameter = value within the default tolerance

Variable

Parameter

Parameters

Maximum Number of Iterations: 10

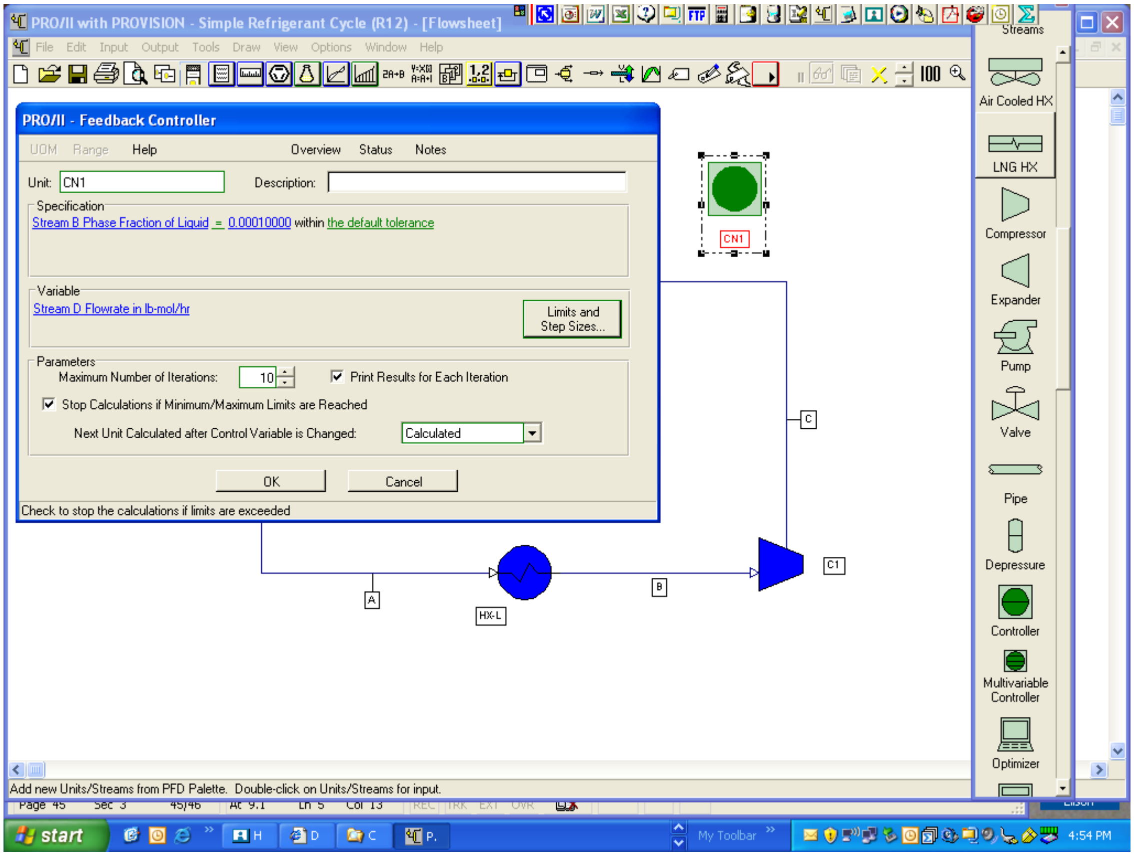
☑ Print Results for Each Iteration

☐ Stop Calculations if Minimum/Maximum Limits are Reached

Next Unit Calculated after Control Variable is Changed: Calculated

Add new Units/Streams from PFD Palette. Double-click on Units/Streams for input.

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 - 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

Other more complex refrigeration cycles:

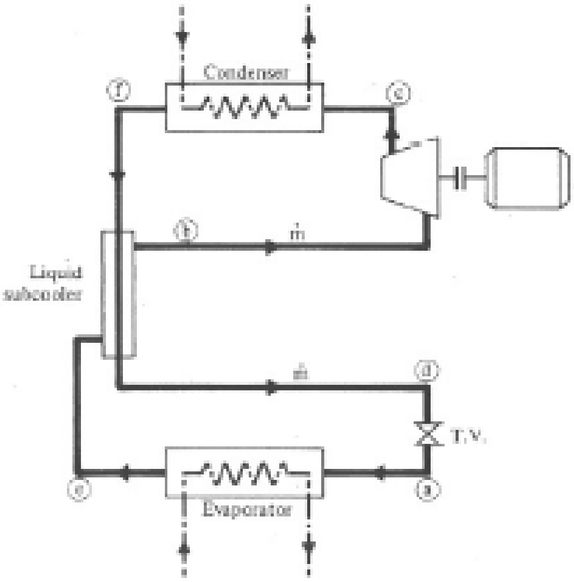


Figure 7: *Liquid sub-cooling in a refrigeration cycle.*

The corresponding TS and P-H diagrams are shown in the next figure. Since we are using the vapor (at the lower pressure) to sub-cool, there is a gain in q_L at the expense of a slight increase in work. Whether there is a gain, it depends on the fluid and the sub-cooled temperature choice.

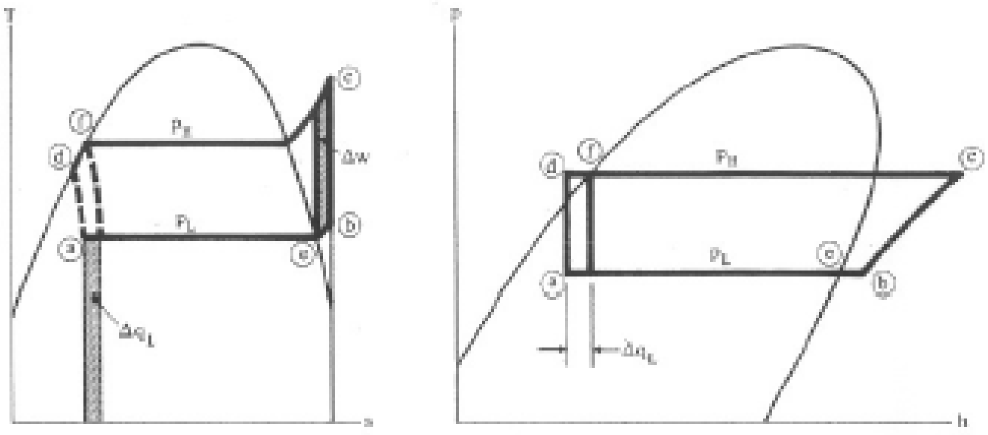


Figure 8: *TS and P-H diagram for liquid sub-cooling in a refrigeration cycle.*

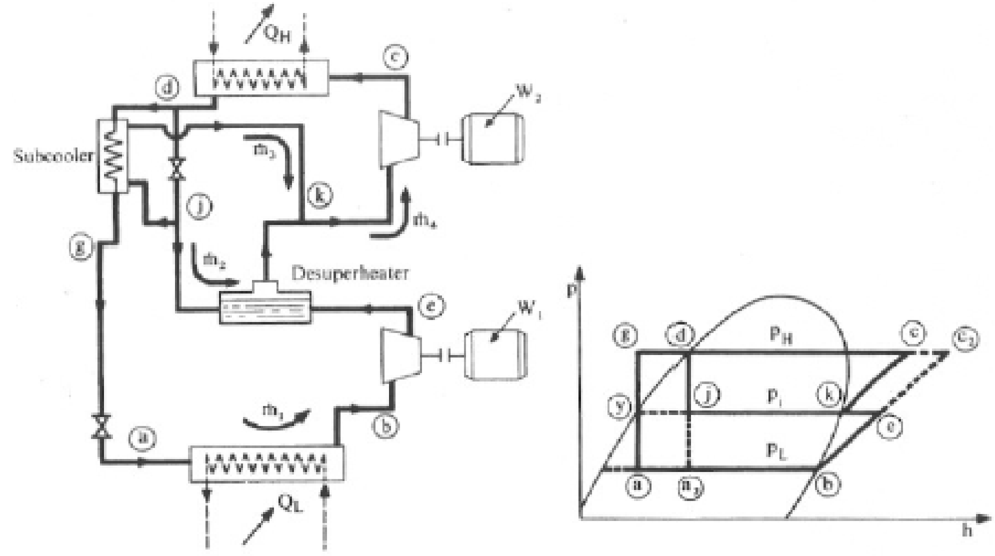


Figure 9: *One Stage subcooler-desuperheater refrigeration cycle.*

Consider now a multistage situation in which two cycles are combined. One reason that multistage cycles are used is because one cycle may require more than one compressor as the compression ratio for one may get to be too high. Instead of putting compressors in series, one could split the work among two compressors and actually increase the COP.

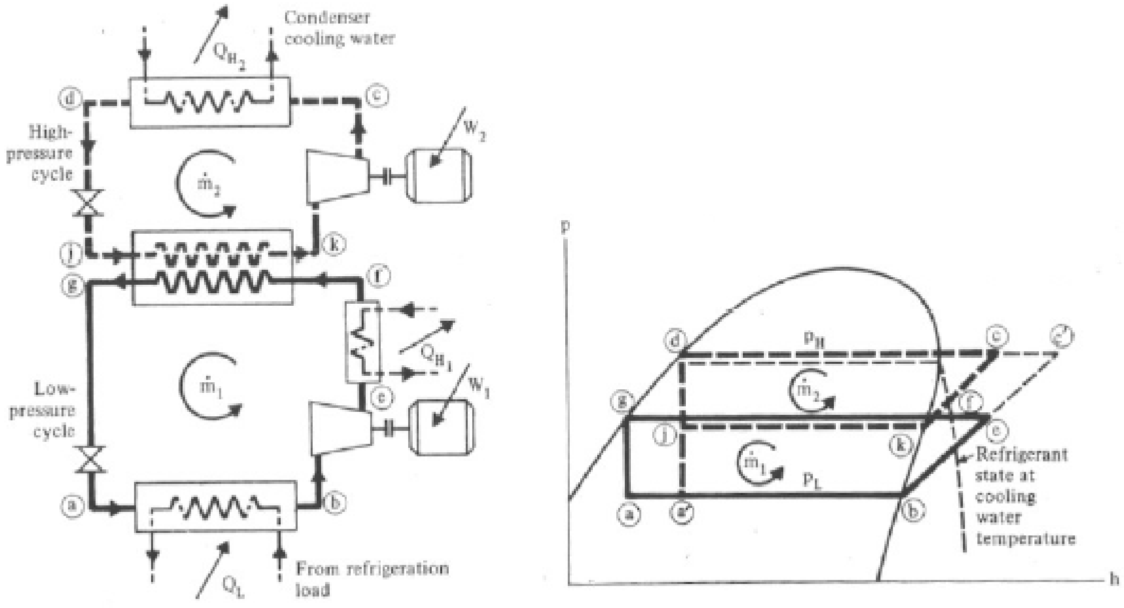


Figure 10: *Two Stage refrigeration cycle.*

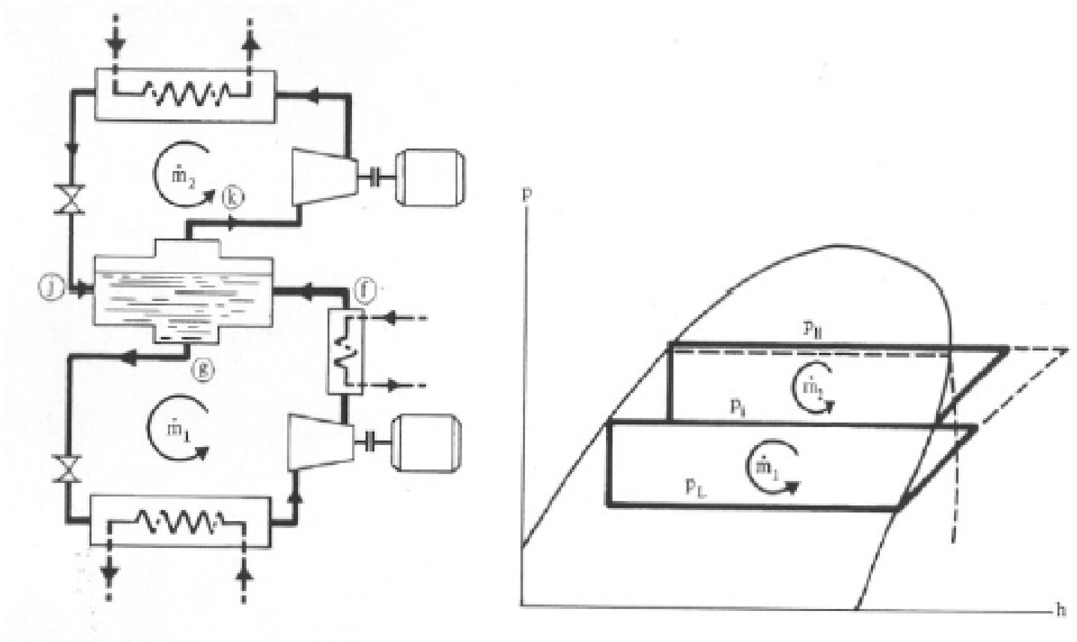


Figure 11: *Open flash two stage refrigeration cycle.*

This actually requires one fluid, but eliminates the need for the upper cycle to have a lower temperature for proper heat exchange, thus reducing work. Besides, a flash tank is cheaper than a heat exchanger.