Simulation of Vapor Recompression Refrigeration Cycle

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조 정 호

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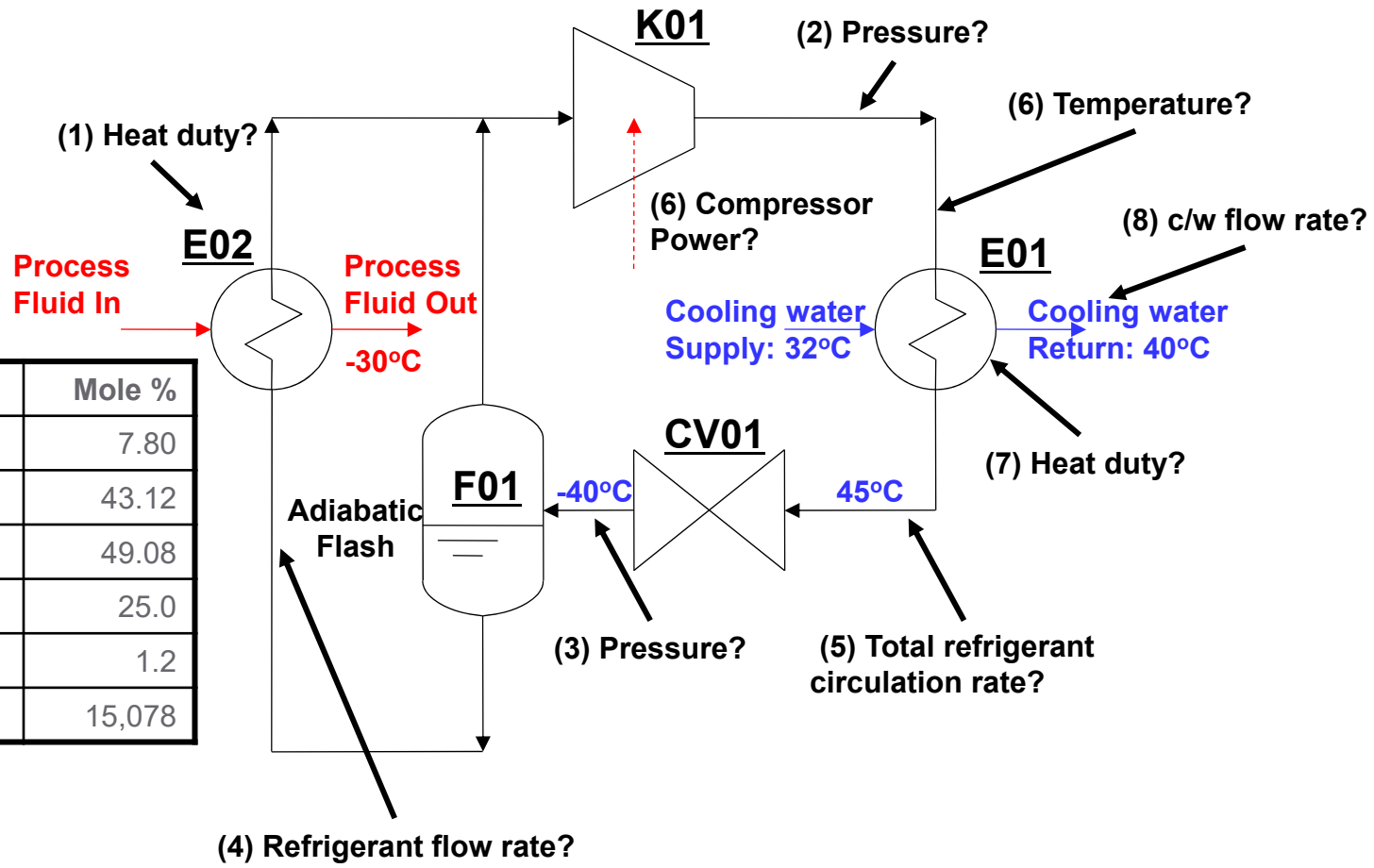
1 Estimation of the Evaporator Heat Duty

Refrigeration Cycle Example:



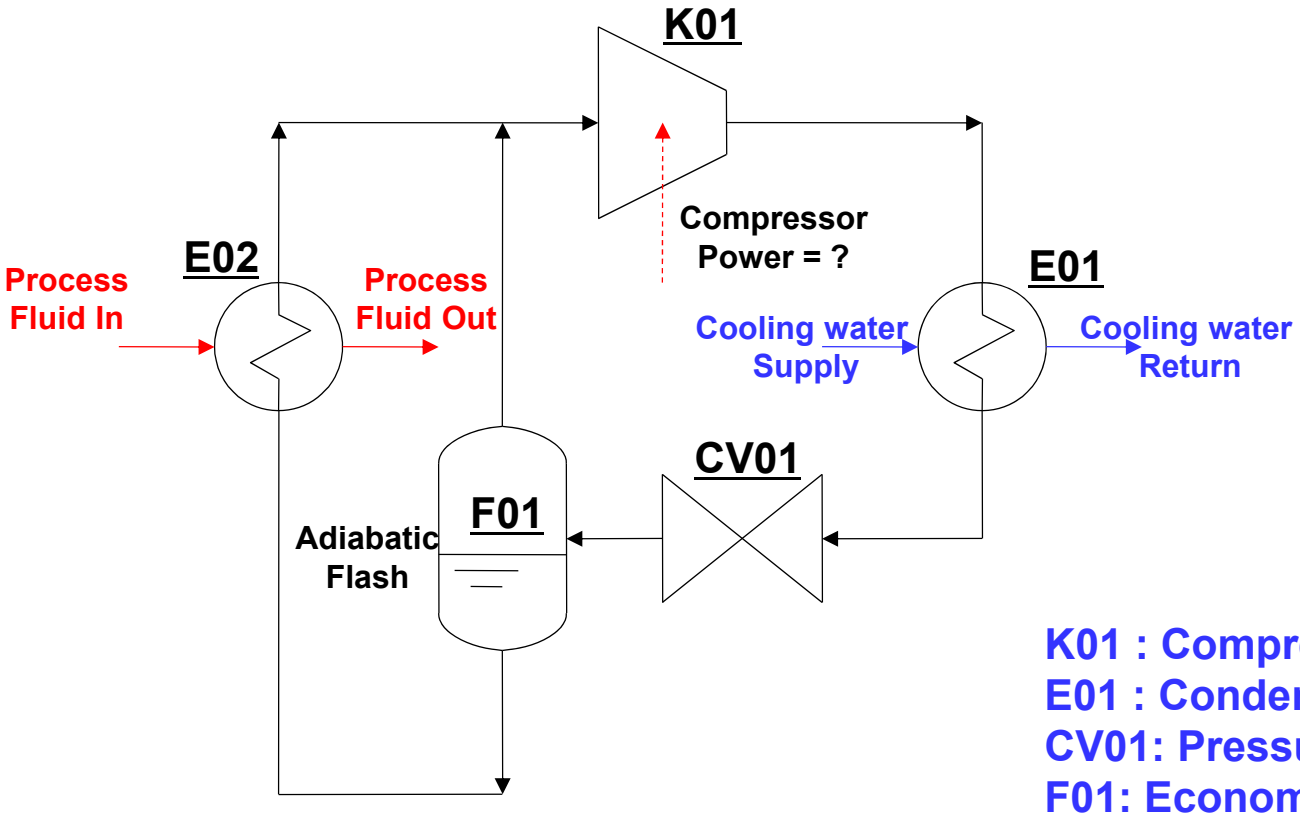
Component	Mole %
C3	7.80
IC4	43.12
NC4	49.08
Temperature (°C)	25.0
Pressure (bar)	1.2
Flow Rate (Kg/hr)	15,078

Use Peng-Robinson Equation of State.

Refrigeration Cycle Example:

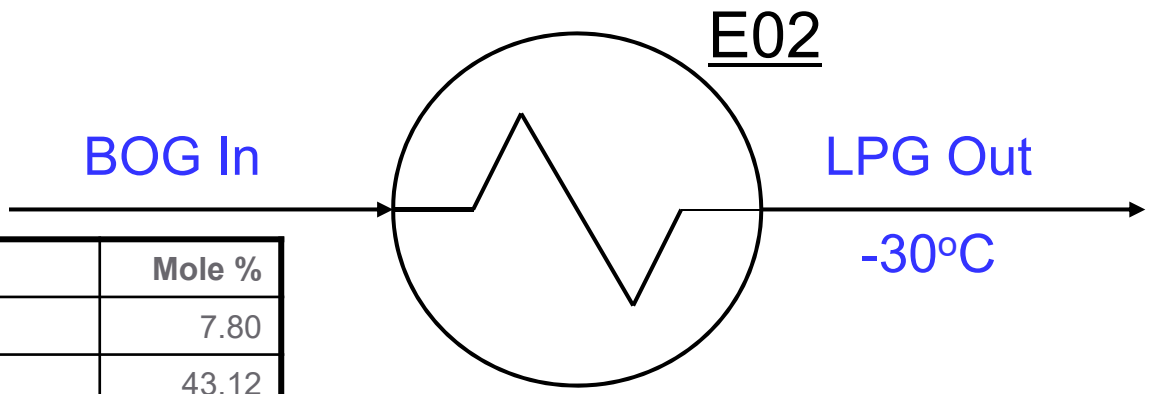
Step	Contents
0	• Draw a schematic diagram for vapor recompression refrigeration cycle • Explain the principles of the propane refrigeration cycle
1	• Estimate the heat duty of the evaporator in 10^6 Kcal/hr.
2	• Determine the discharge pressure of the compressor.
3	• Determine the outlet pressure of the expansion valve.
4	• Determine the refrigerant mass flow rate feeding to the evaporator.
5	• Determine the total refrigerant circulation rate.
6	• Estimate the compressor power. Assume that that adiabatic efficiency of the compressor is 70%. • Estimate the compressor discharge temperature.
7	• Determine the heat duty of the condenser.
8	• Determine the cooling water consumptions in tons per hour.
9	• Complete the overall refrigeration cycle in one PRO/II file and compare its results with each step-by-step simulation results.
10	• Complete the overall refrigeration cycle for mixed refrigerants and compare their results with a single refrigerant simulation results.

Step 0: Draw a Schematic Diagram of the Vapor Refrigeration Cycle Using Propane



K01 : Compressor
E01 : Condenser
CV01: Pressure Let-down Valve
F01: Economizer
E02: Evaporator

Step 1: Evaporator Heat Duty?



Component	Mole %
C3	7.80
IC4	43.12
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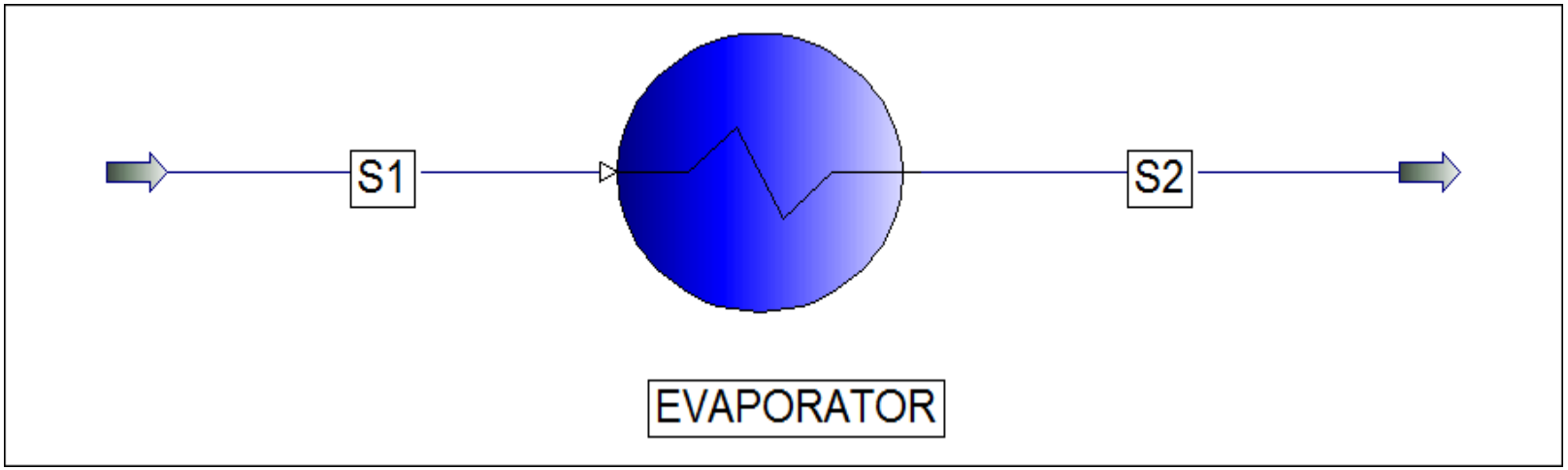
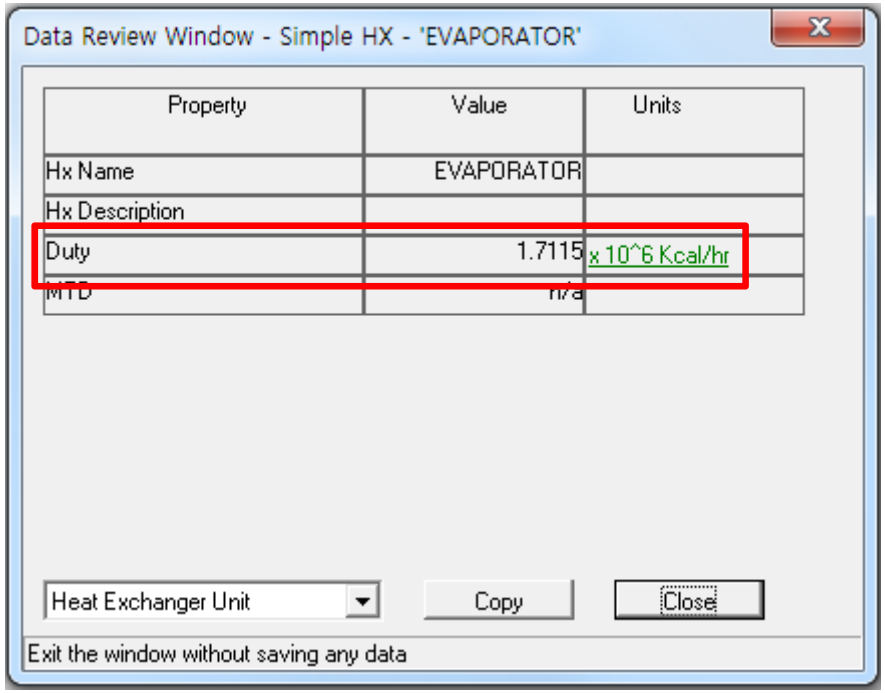
Step 1: Flow Sheet Drawing



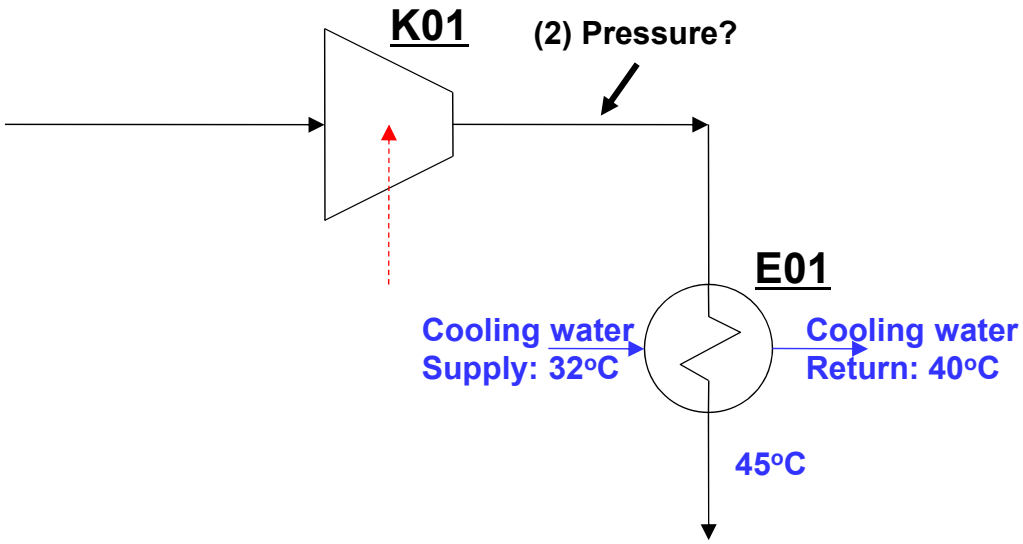
Step_01_Evaporator heat duty.prz

Step 1: Evaporator Heat Duty



2 Determination of the Compressor Discharge Pressure

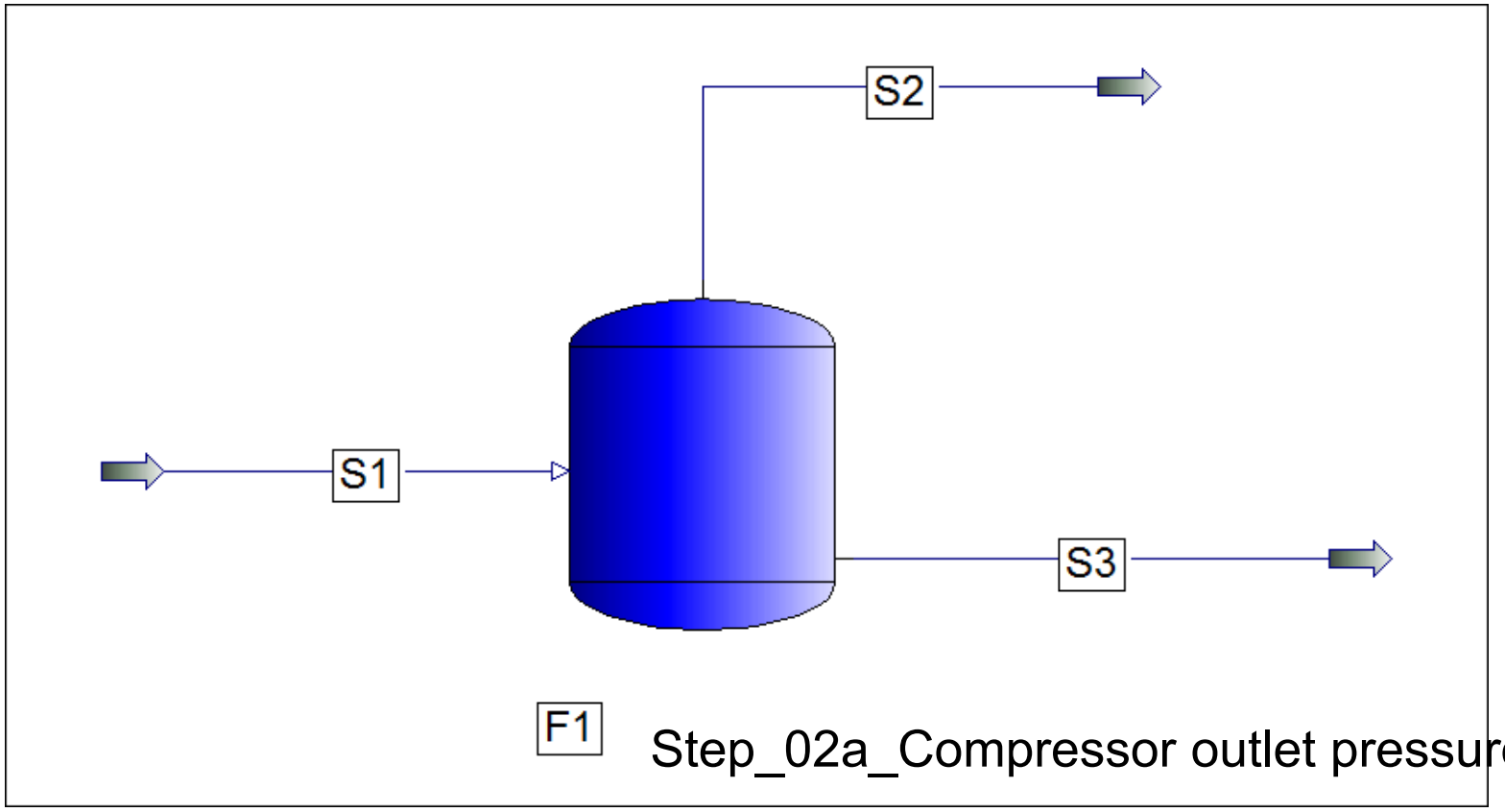
Step 2: Compressor Discharge Pressure Determination



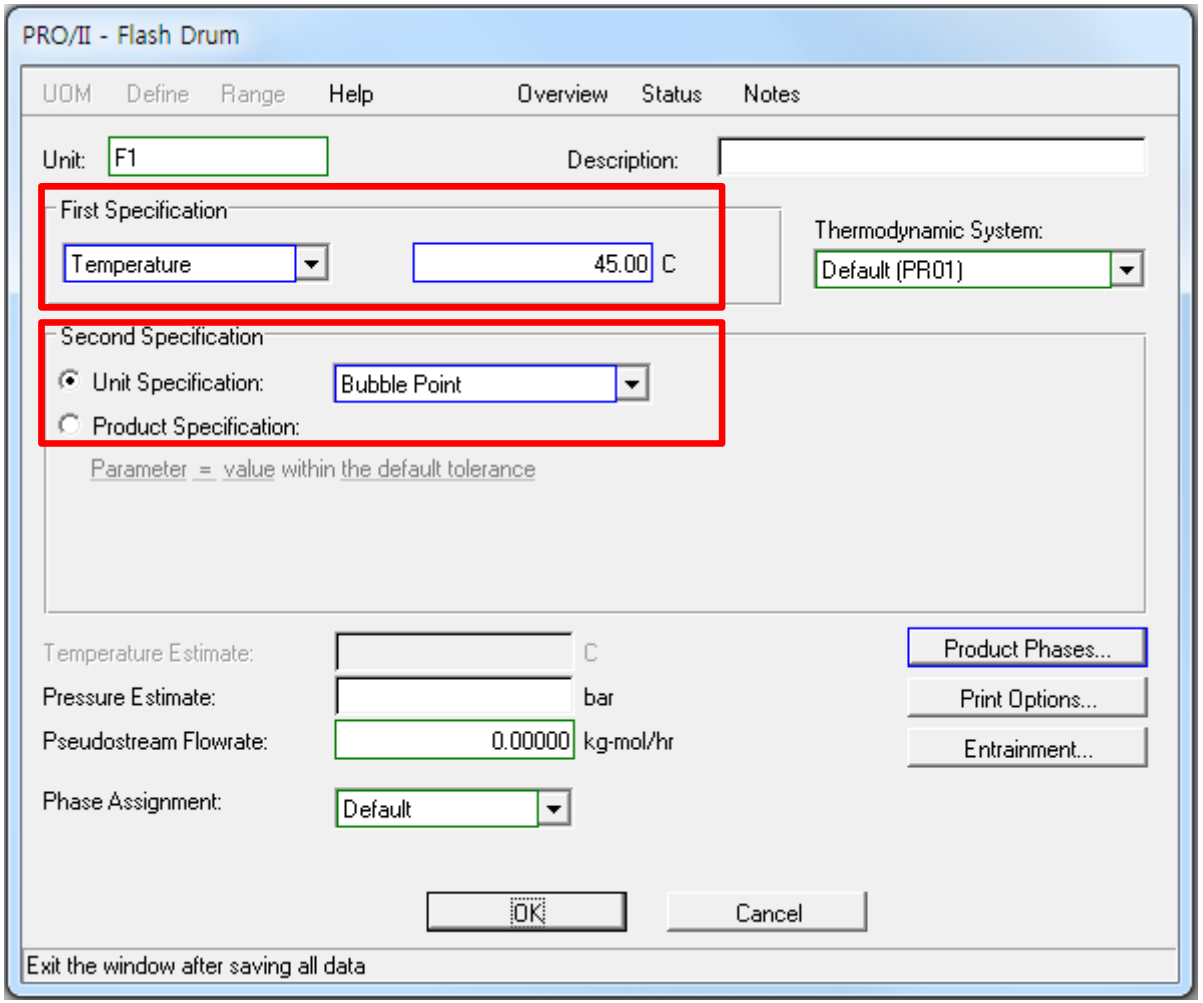
- Compressor discharge pressure is equal to….
  - When the propane refrigerant is cooled down to 45°C, it should be condensed and liquefied to saturate liquid state.
  - In principle, compressor discharge pressure is equal to the bubble point pressure of propane at 45°C using Peng-Robinson equation of state.

Step 2a: Compressor Discharge Pressure: Flash Calculation

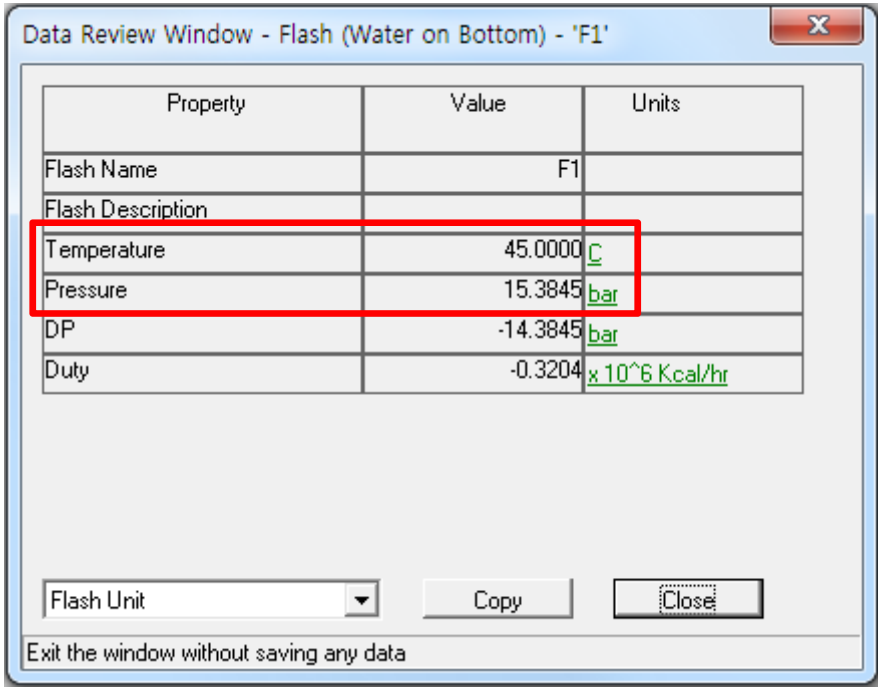
- Step 2a: Using Flash module
  - Bubble pressure calculation of propane at 45°C using Peng-Robinson equation of state.



Step 2a: Compressor Discharge Pressure: Flash Calculation

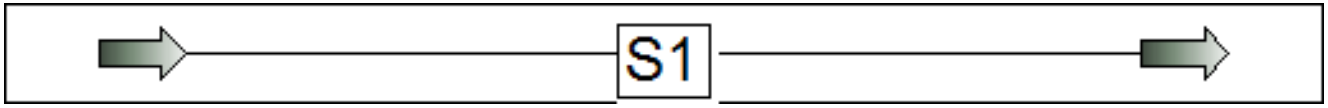


Step 2a: Compressor Discharge Pressure: Flash Calculation



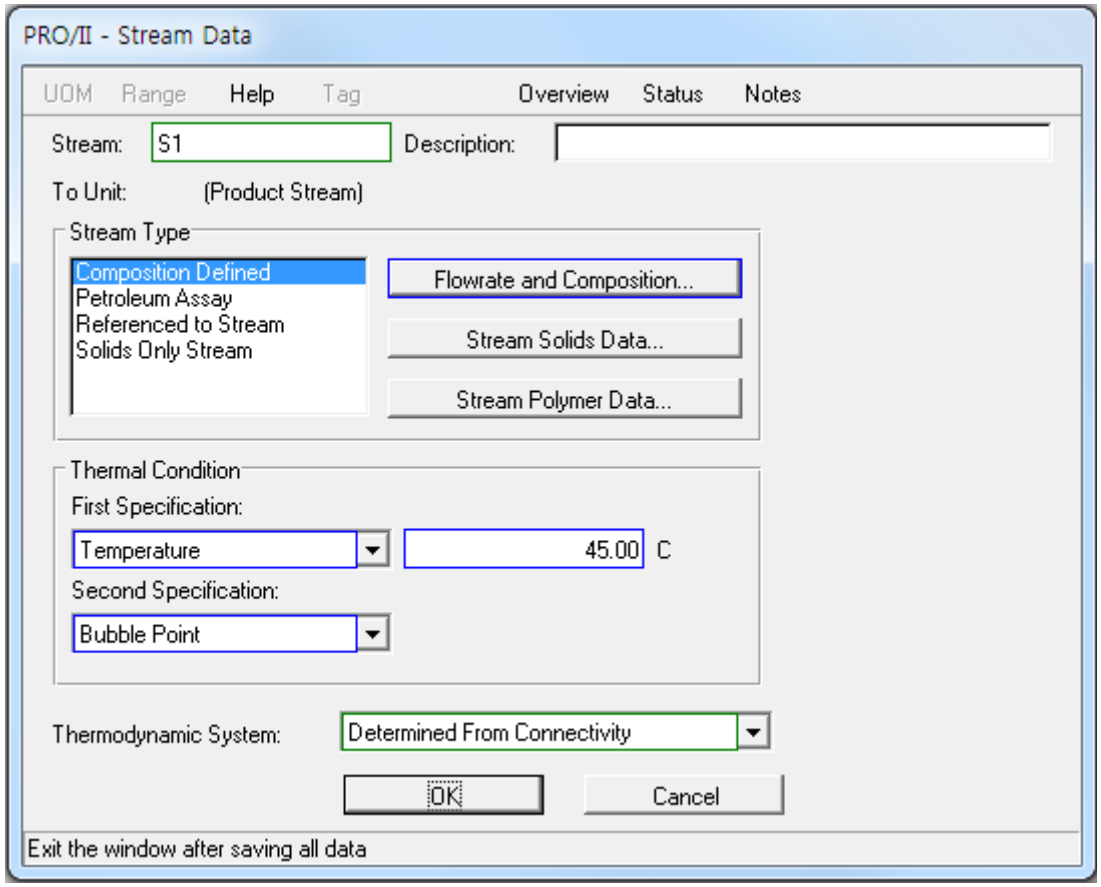
Step 2b: Compressor Discharge Pressure: Feed Calculation

- Step 2b: Using Feed stream only
  - Feed stream thermal condition: Bubble point at 45^{o}C using Peng-Robinson equation of state.

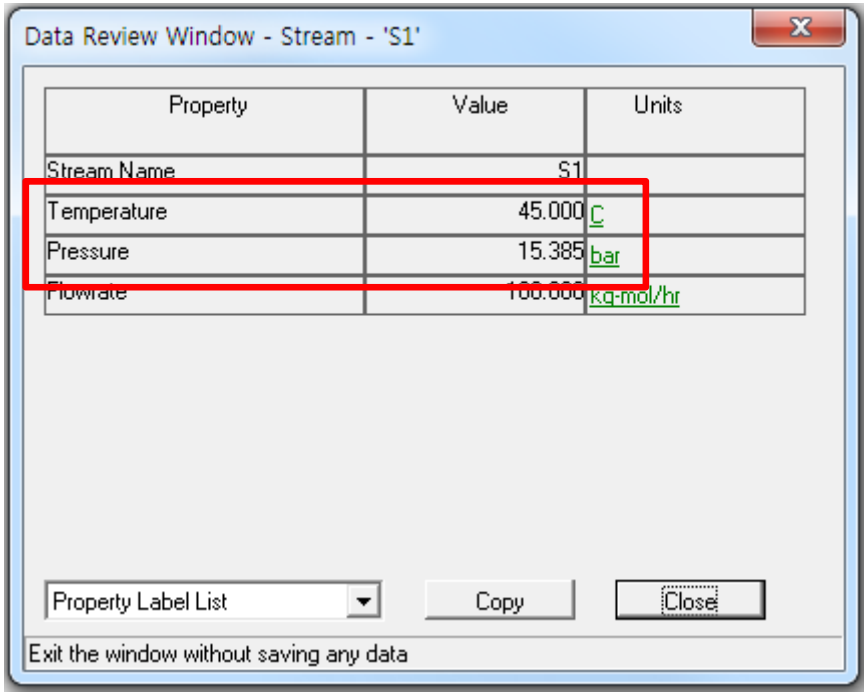


Step_02b_Compressor outlet pressure.prz

Step 2b: Compressor Discharge Pressure: Feed Calculation

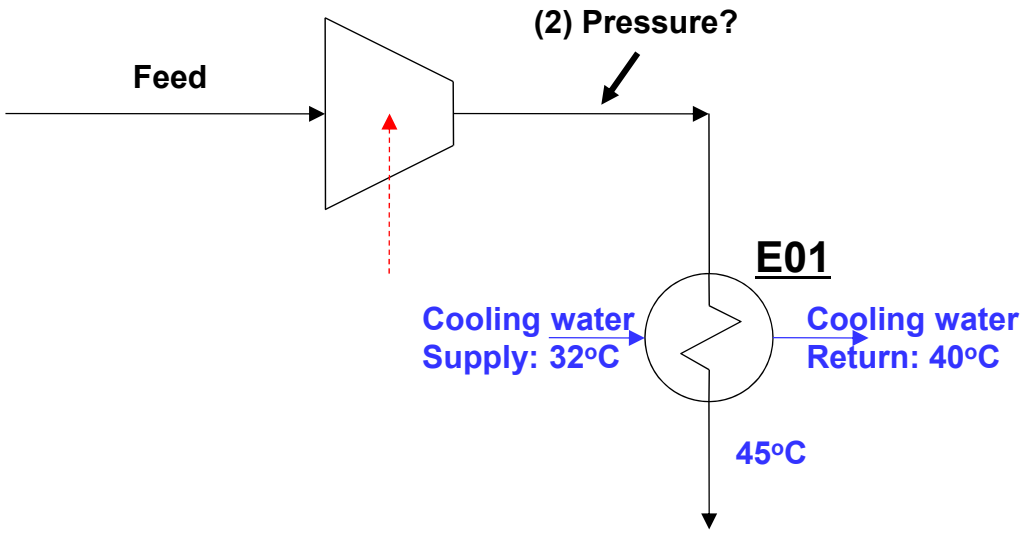


Step 2b: Compressor Discharge Pressure: Feed Calculation

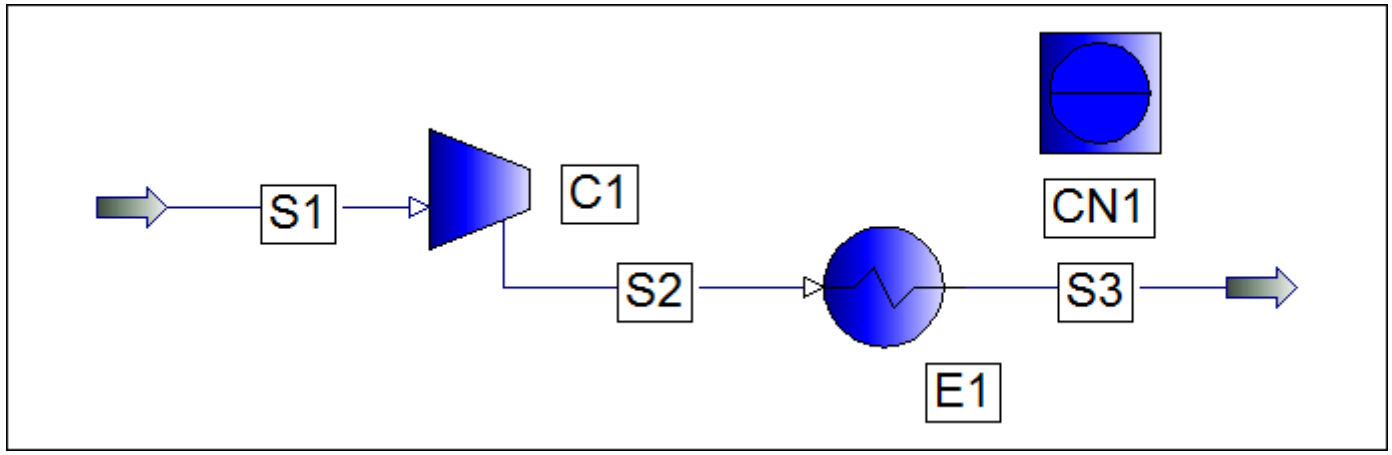


Step 2c: Compressor Discharge Pressure: Using Controller

- Step 2c: Compressor and condenser system with controller
  - Feed stream thermal condition: Dew point at -40^{o}C
  - Condenser outlet condition: saturated liquid state
  - Controller: Specify E01 outlet stream temperature as 45^{o}C by varying the compressor discharge pressure.

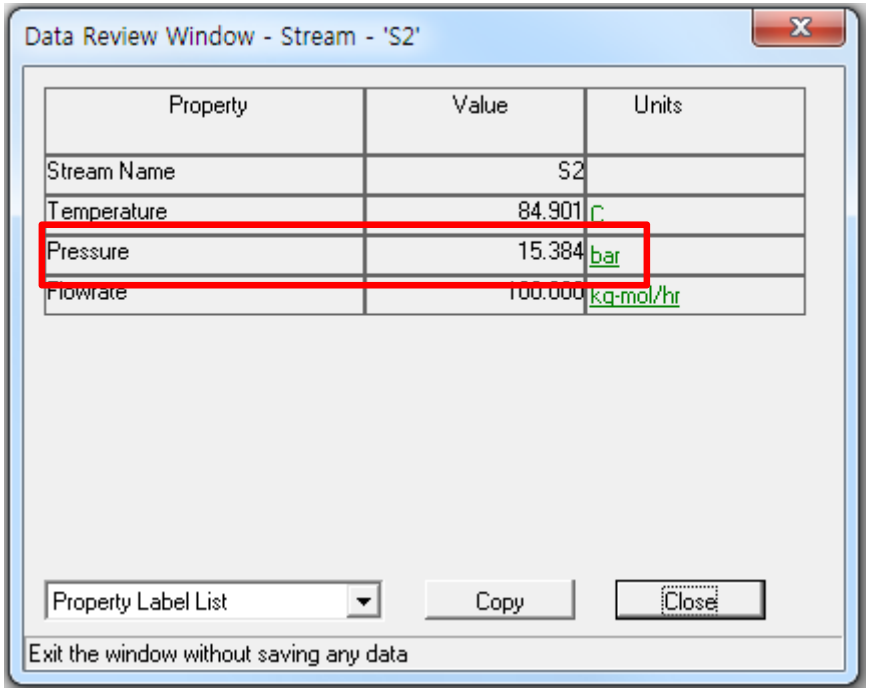


Step 2c: Compressor Discharge Pressure: Using Controller



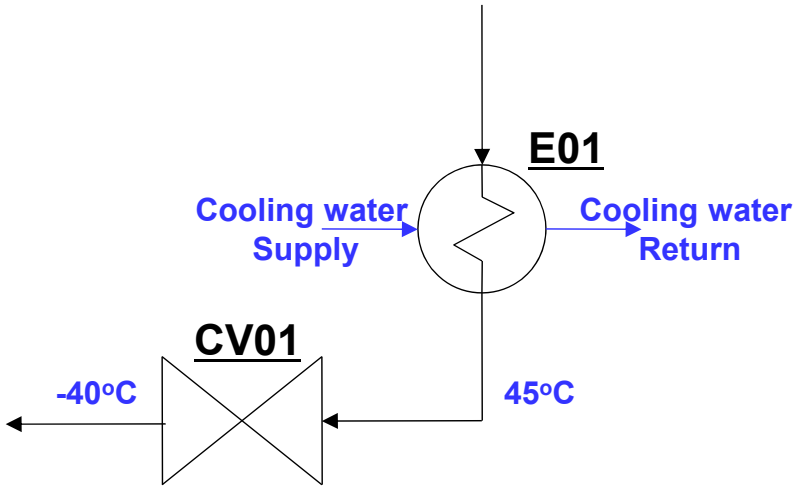
Step_02c_Compressor outlet pressure with controller.prz

Step 2c: Compressor Discharge Pressure: Using Controller



3 Determination of the Valve Outlet Pressure

Step 3: Expansion Valve Outlet Pressure

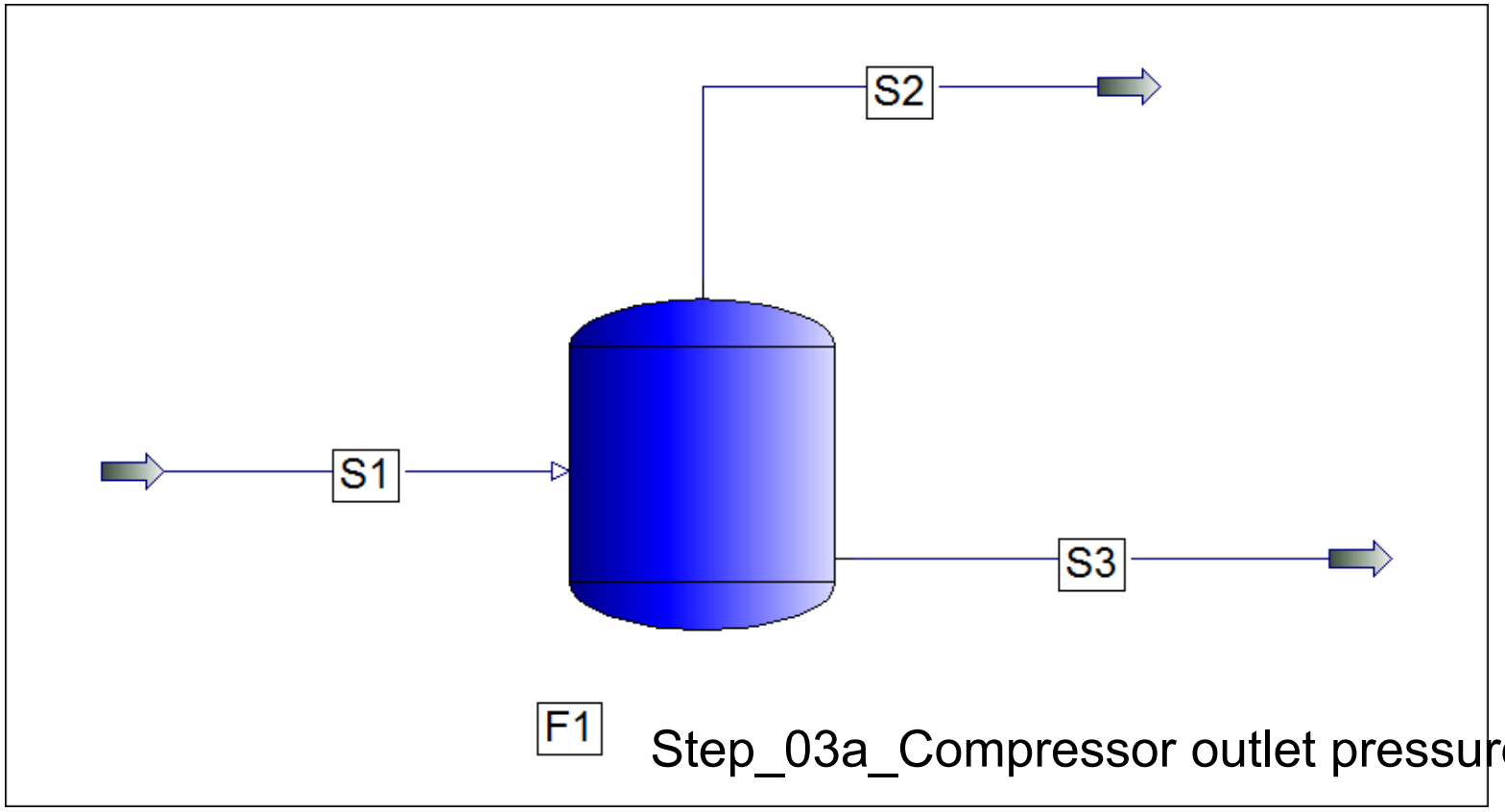


- Expansion valve outlet pressure is equal to….
  - When the propane refrigerant is expanded to a lower pressure from the saturated liquid state at 45°C, propane temperature should be lowered to -40°C.
  - In principle, expansion valve outlet pressure is equal to the dew point pressure of propane at -40°C using Peng-Robinson equation of state.

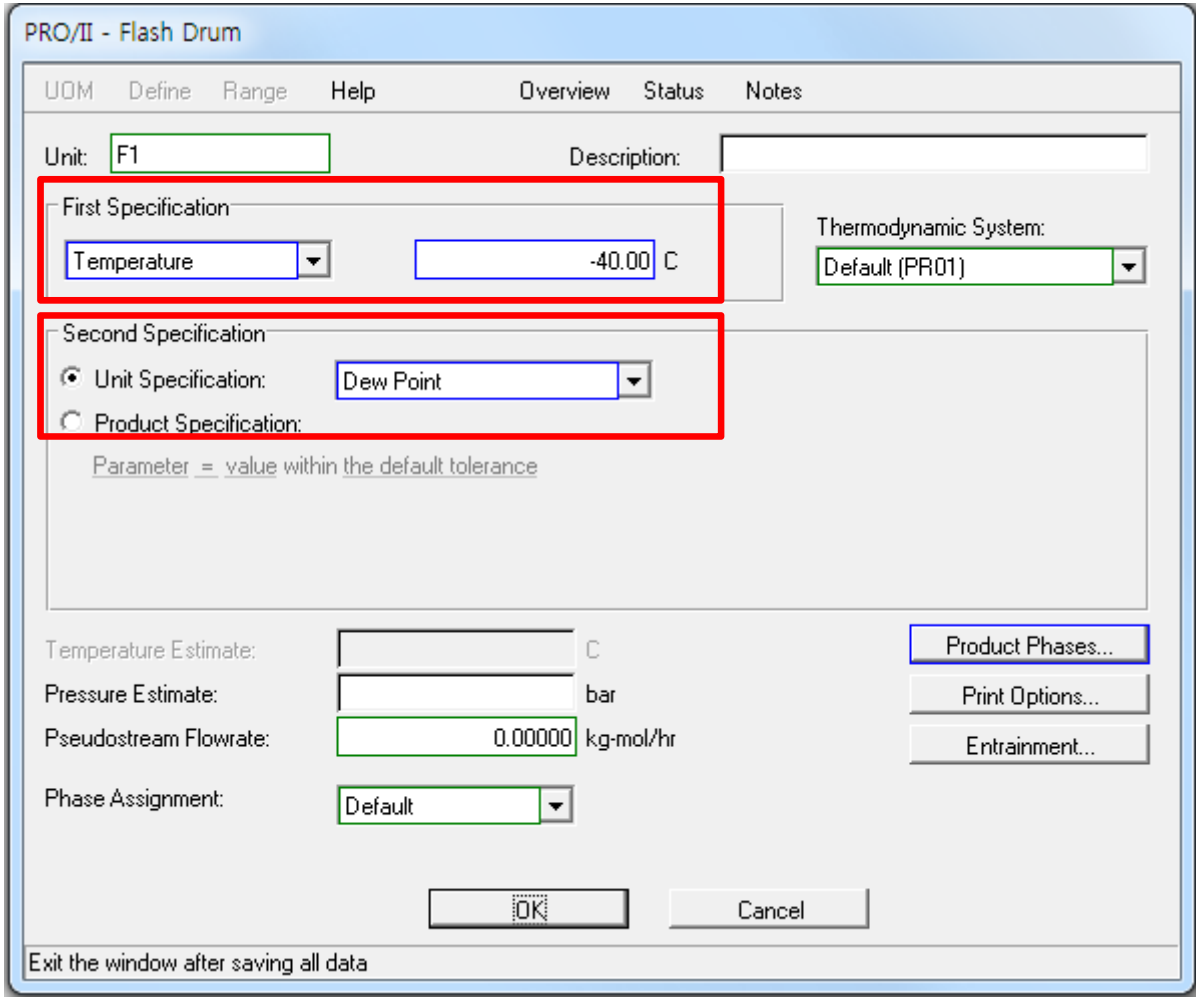
Step 3a: Expansion Valve Outlet Pressure: Flash Calculation

Step 3a: Using Flash module

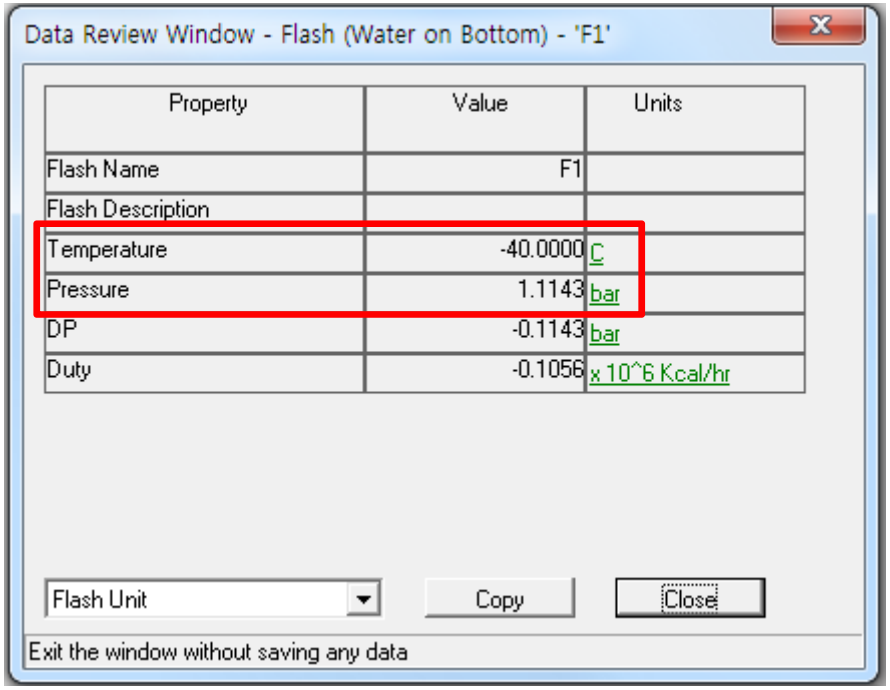
- Dew pressure calculation of propane at -40°C using Peng-Robinson equation of state.



Step 3a: Expansion Valve Outlet Pressure: Flash Calculation

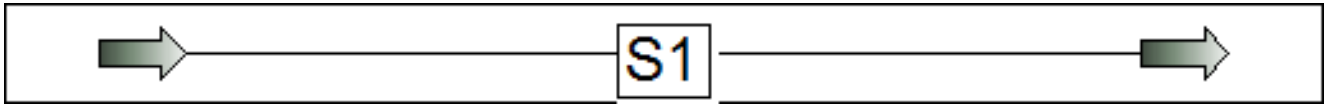


Step 3a: Expansion Valve Outlet Pressure: Flash Calculation



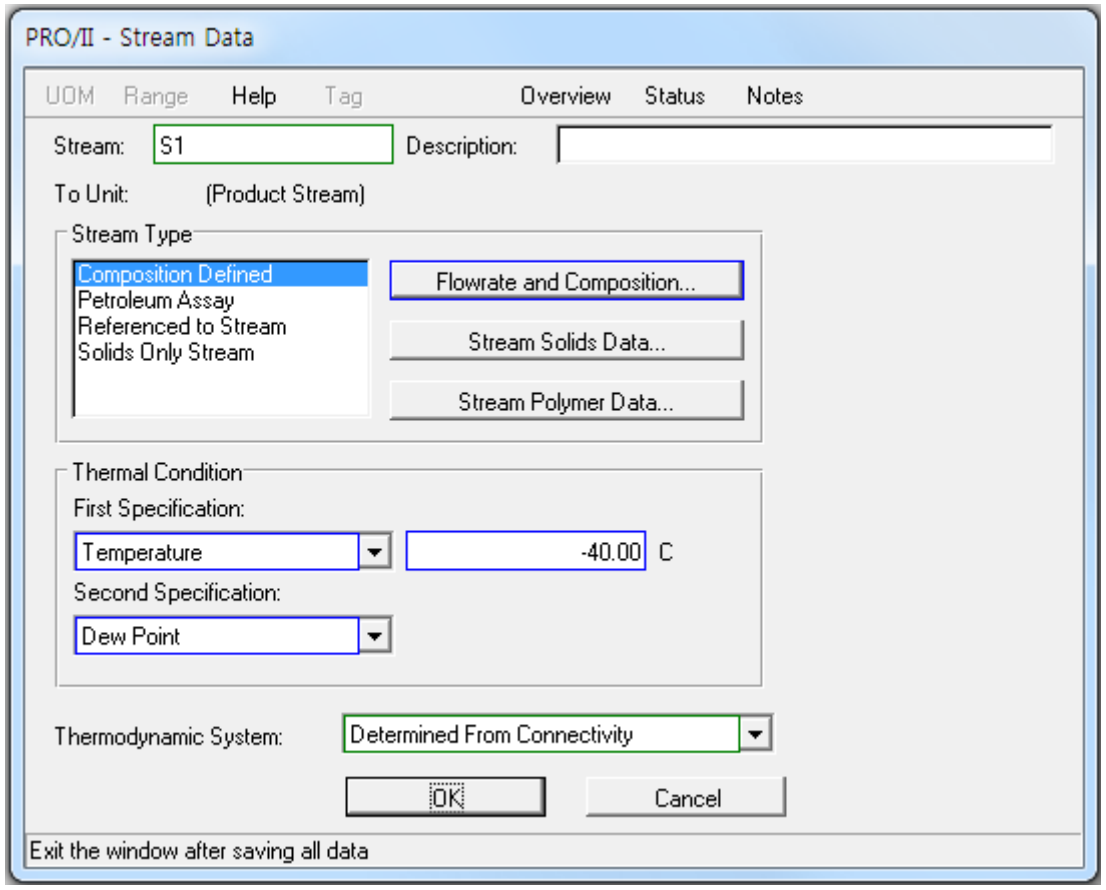
Step 3b: Expansion Valve Outlet Pressure: Feed Flash

- Step 3b: Using Feed stream only
  - Feed stream thermal condition: Bubble point at 45^{o}C using Peng-Robinson equation of state.

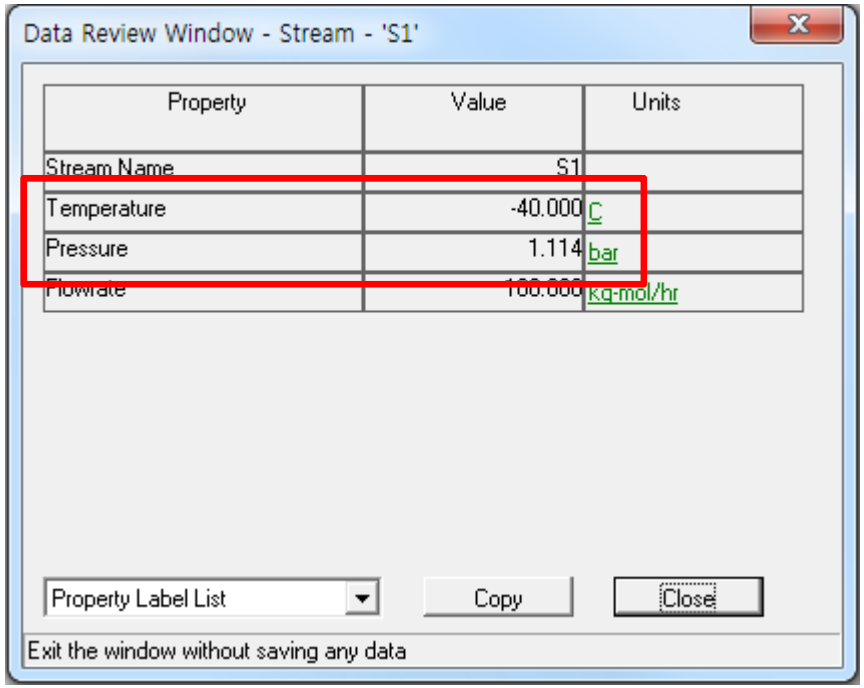


Step_03b_Compressor outlet pressure.prz

Step 3b: Expansion Valve Outlet Pressure: Feed Flash

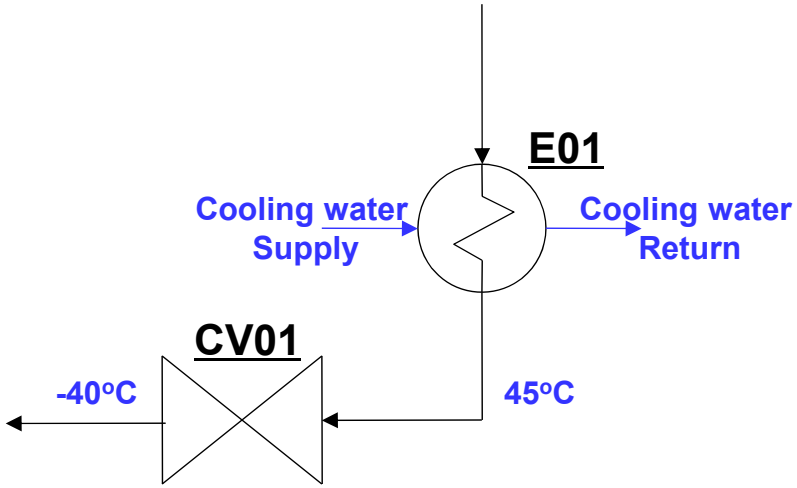


Step 3b: Expansion Valve Outlet Pressure: Feed Flash

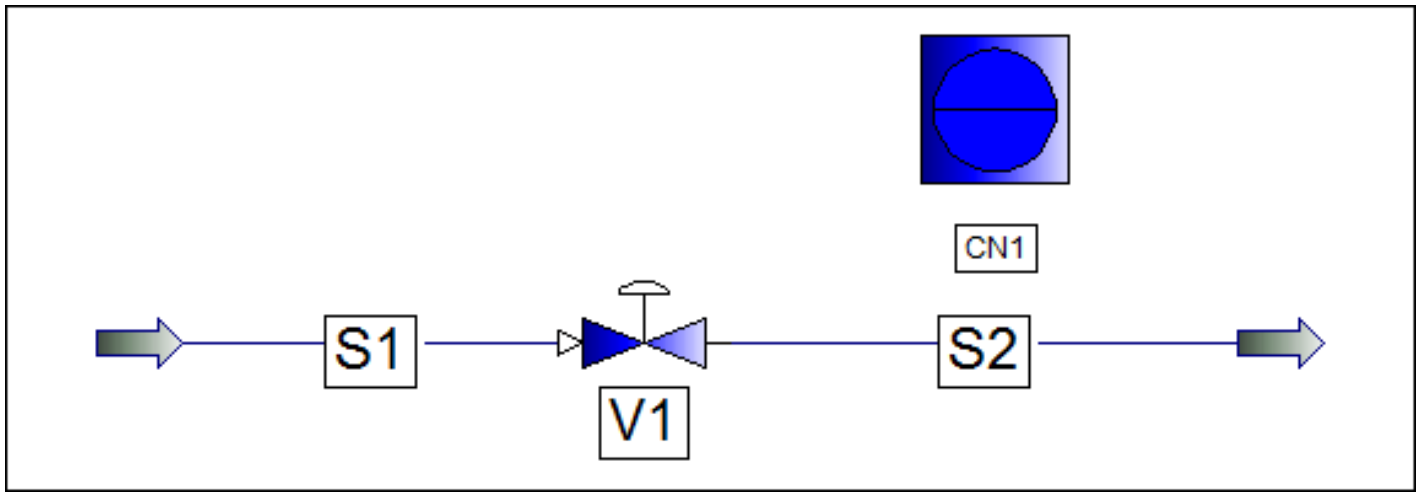


Step 3c: Expansion Valve Outlet Pressure: Using Controller

- Step 3c: Compressor and condenser system with controller
  - Feed stream thermal condition: Bubble point at 45^{o}C
  - Controller: Specify CV01 outlet stream temperature as -40^{o}C by varying the expansion valve outlet pressure.

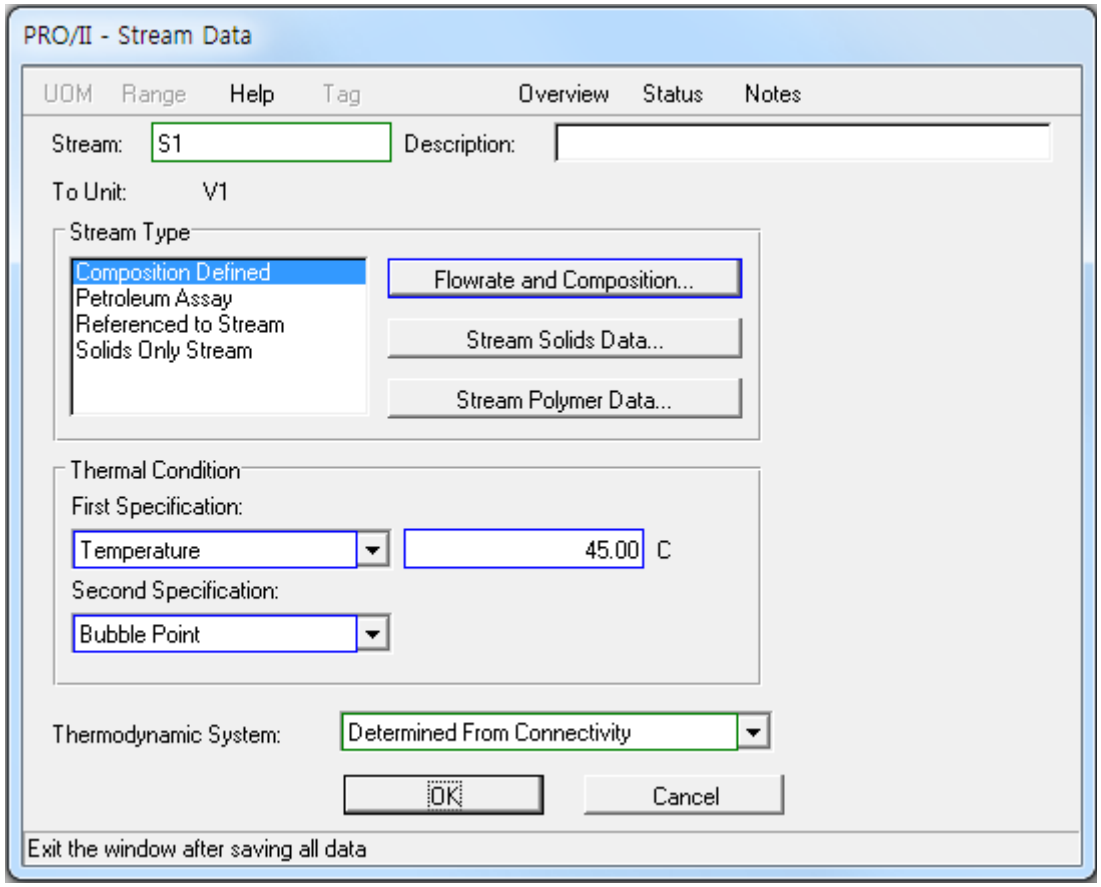


Step 3c: Expansion Valve Outlet Pressure: Using Controller

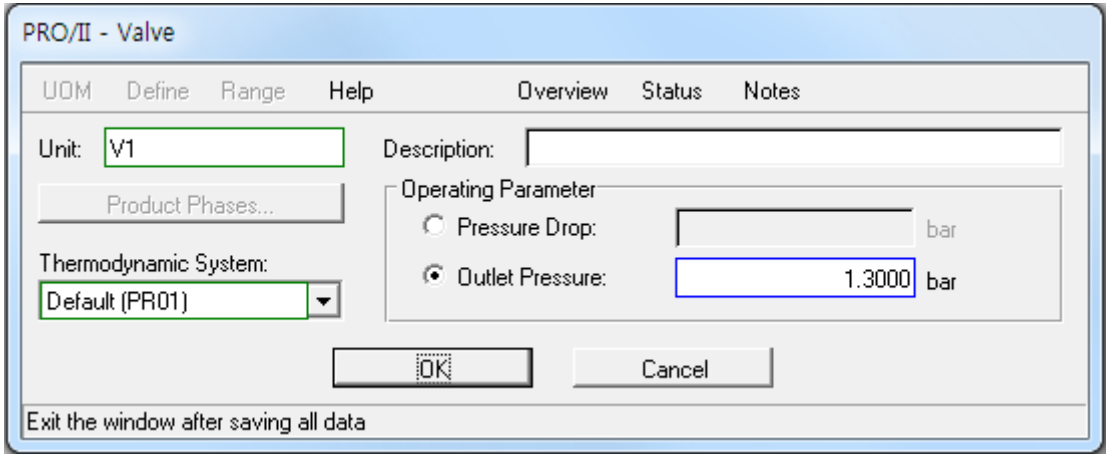


Step_03c_Expansion valve outlet pressure with controller.prz

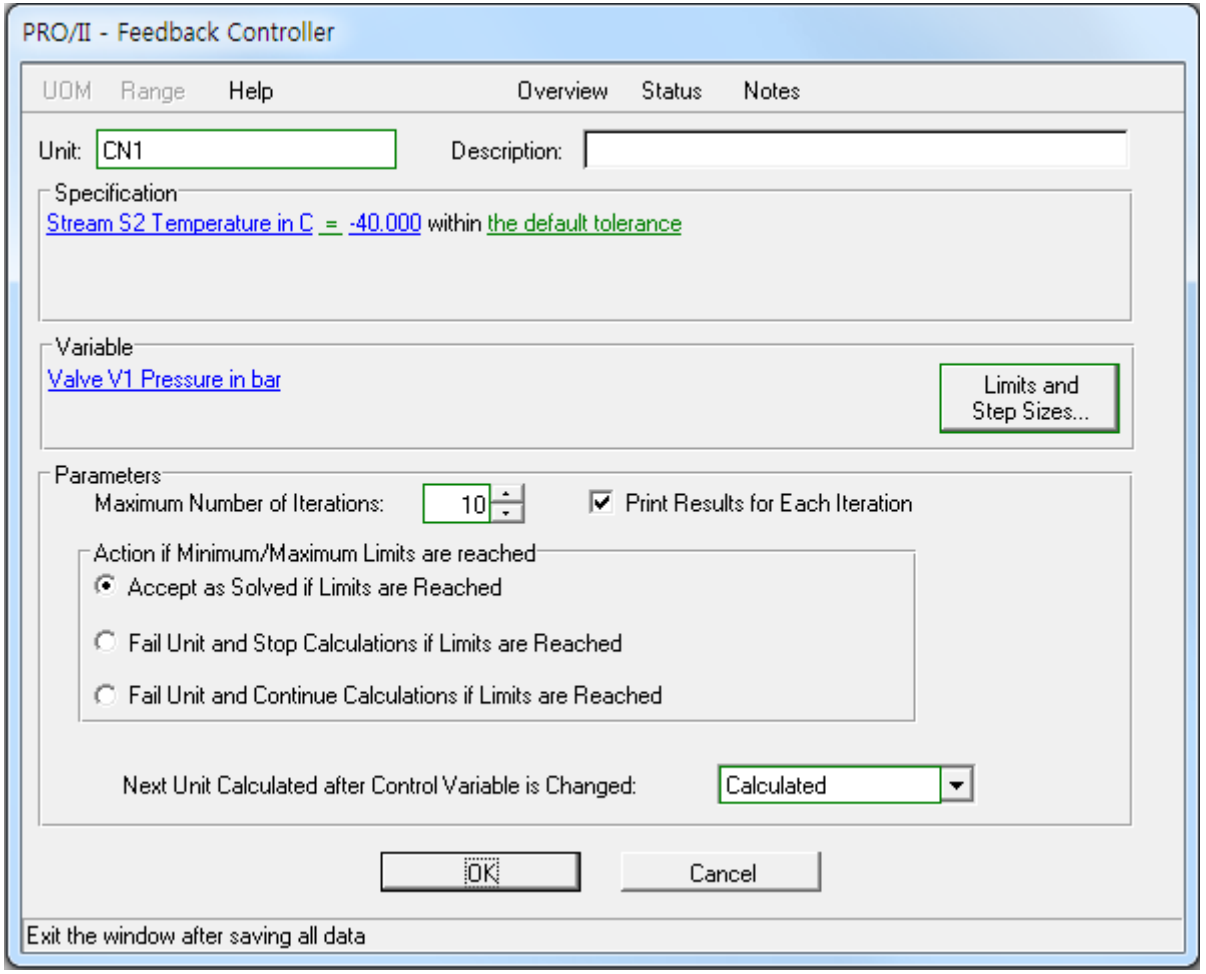
Step 3c: Expansion Valve Outlet Pressure: Using Controller



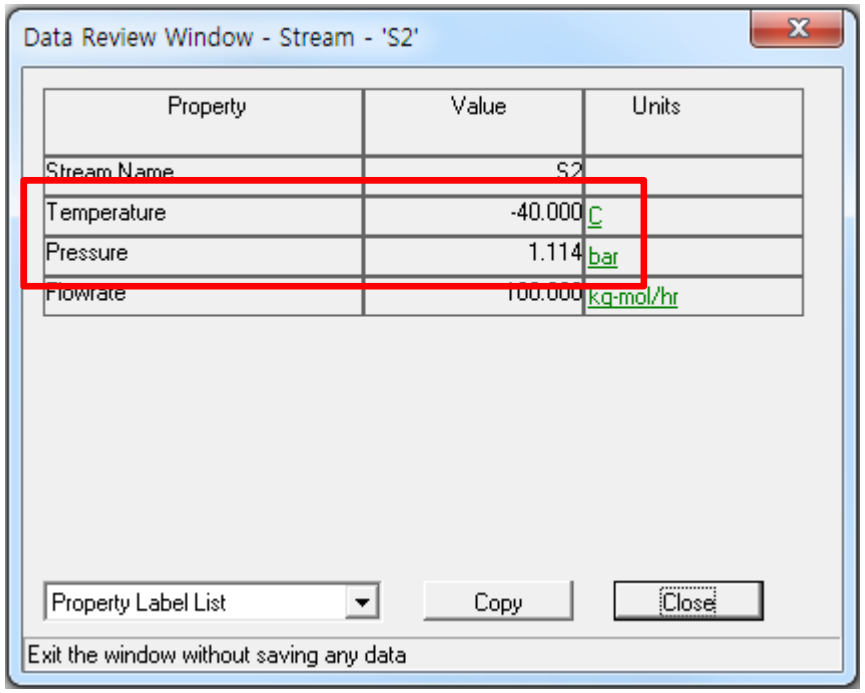
Step 3c: Expansion Valve Outlet Pressure: Using Controller



Step 3c: Expansion Valve Outlet Pressure: Using Controller



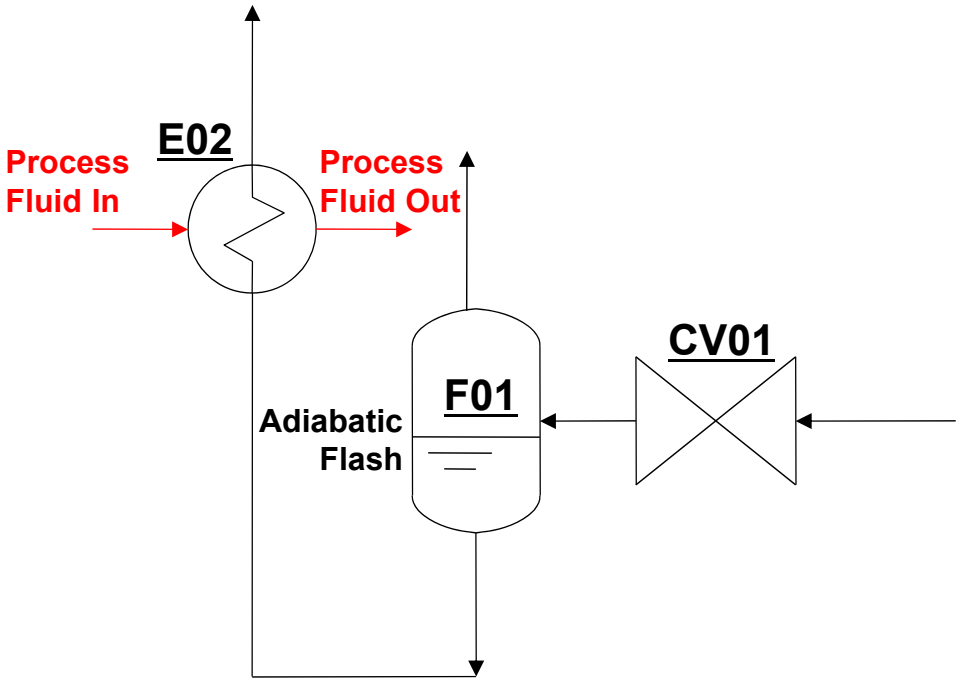
Step 3c: Expansion Valve Outlet Pressure: Using Controller



4 Estimation of the Refrigerant Flow Rate to Evaporator

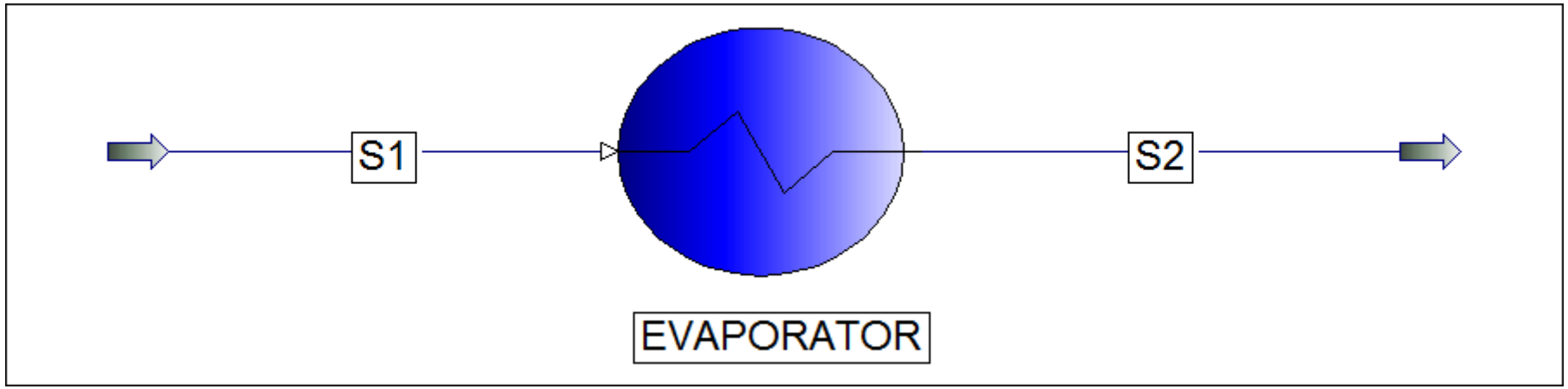
Step 4: Refrigerant Flow Rate to the Evaporator

- Refrigerant flow rate feeding the evaporator
  - Use utility option in evaporator simulation.
  - In principle, expansion valve outlet pressure is equal to the dew point pressure of propane at -40^{o}C using Peng-Robinson equation of state.



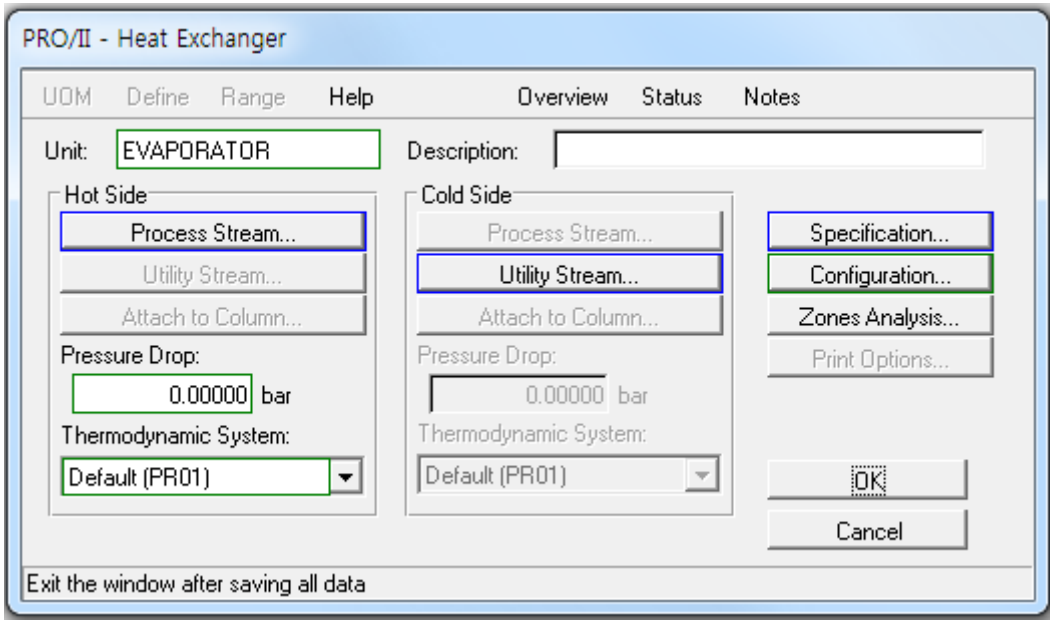
Step 4a: Refrigerant Flow Rate to the Evaporator: Utility

- Step 4a: Use Utility option in HX
  - Choose propane as a refrigerant for cold side stream fluid.

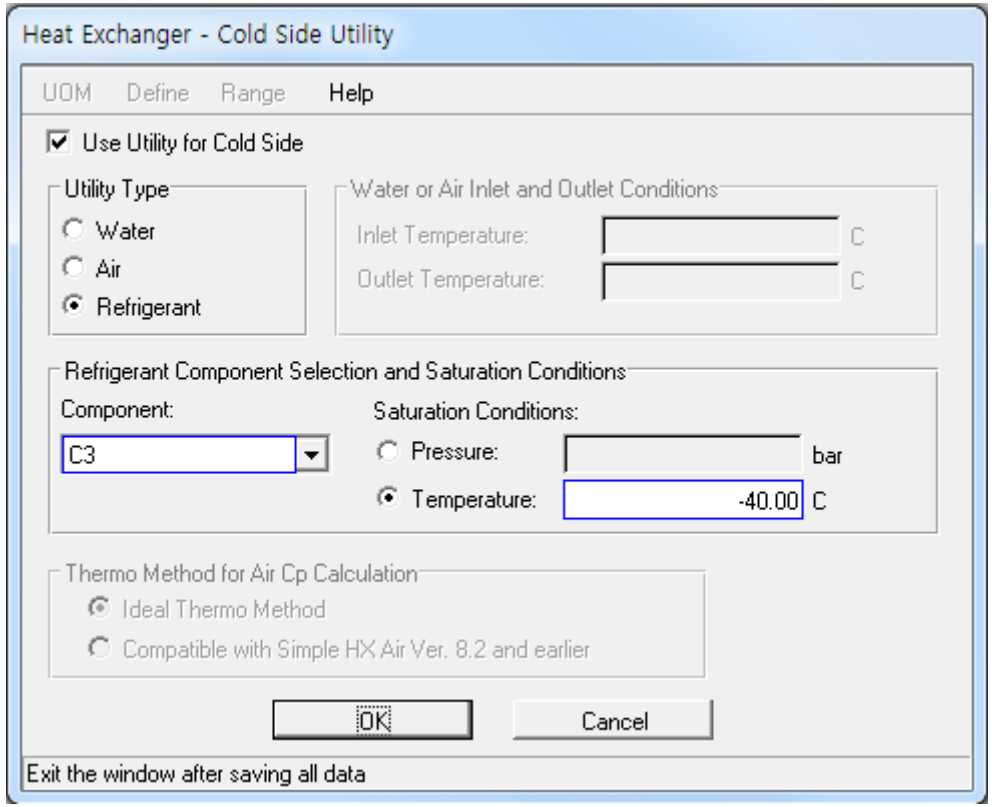


Step_04a_Refrigerant flowrate to the evaporator.prz

Step 4a: Refrigerant Flow Rate to the Evaporator: Utility



Step 4a: Refrigerant Flow Rate to the Evaporator: Utility

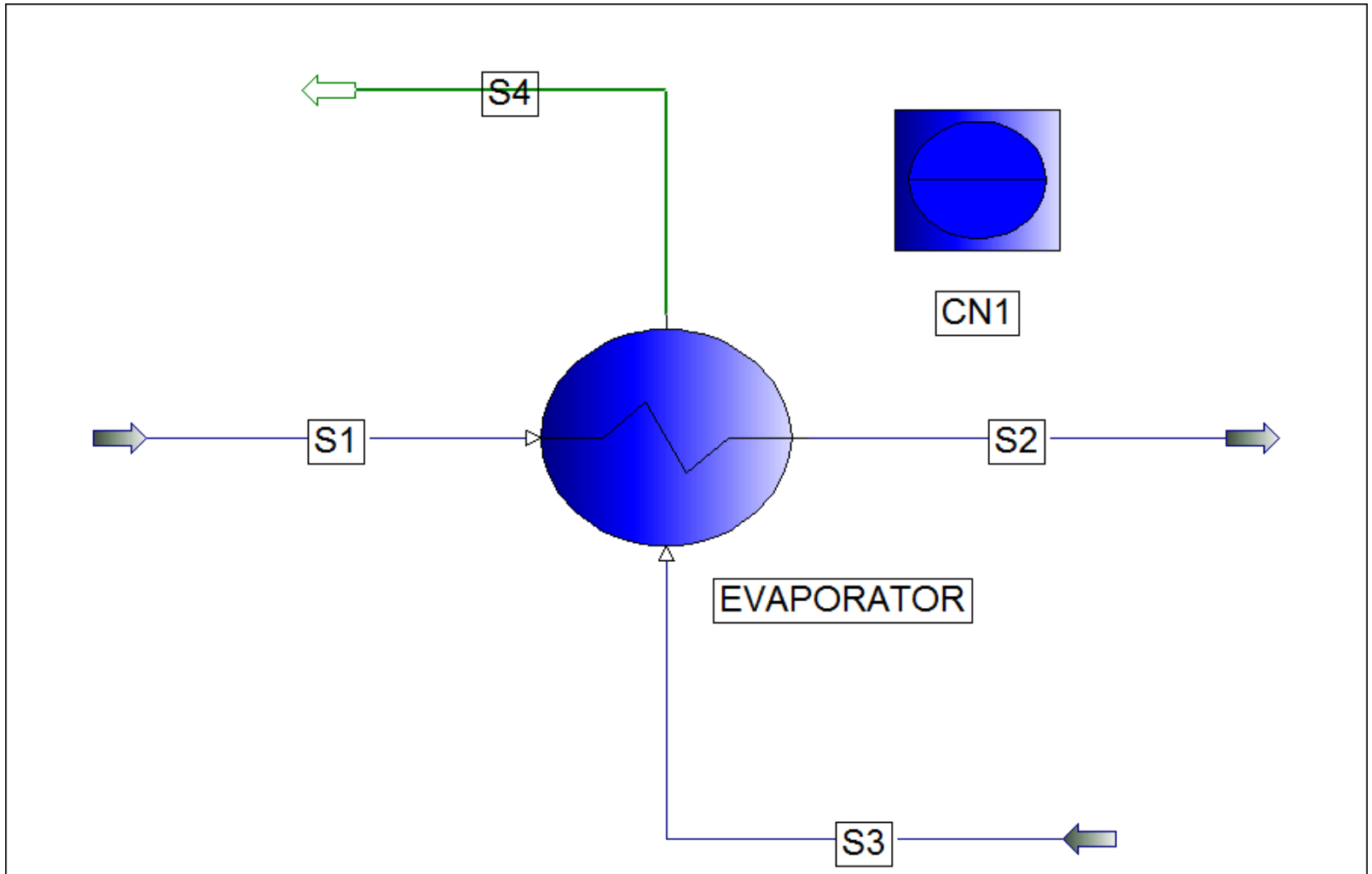


Step 4a: Refrigerant Flow Rate to the Evaporator: Utility

OPERATING CONDITIONS		
DUTY, M*KCAL/HR	**1.712**	
LMTD, C	29.383	
HOT SIDE CONDITIONS	**INLET**	**OUTLET**
FEED	S1	
LIQUID PRODUCT		S2
VAPOR, KG-MOL/HR	264.390	
K*KG/HR	15.078	
CP, KCAL/KG-C	0.404	
LIQUID, KG-MOL/HR		264.390
K*KG/HR		15.078
CP, KCAL/KG-C		0.490
TOTAL, KG-MOL/HR	264.390	264.390
K*KG/HR	15.078	15.078
CONDENSATION, KG-MOL/HR		264.390
TEMPERATURE, C	25.000	-30.000
PRESSURE, BAR	1.200	1.200
COLD SIDE CONDITIONS	**INLET**	**OUTLET**
REFRIGERANT, KG/HR	**16946.501**	**16946.501**
SATURATION PRESSURE, BAR	**1.109**	
SATURATION TEMPERATURE, C	**-40.000**	

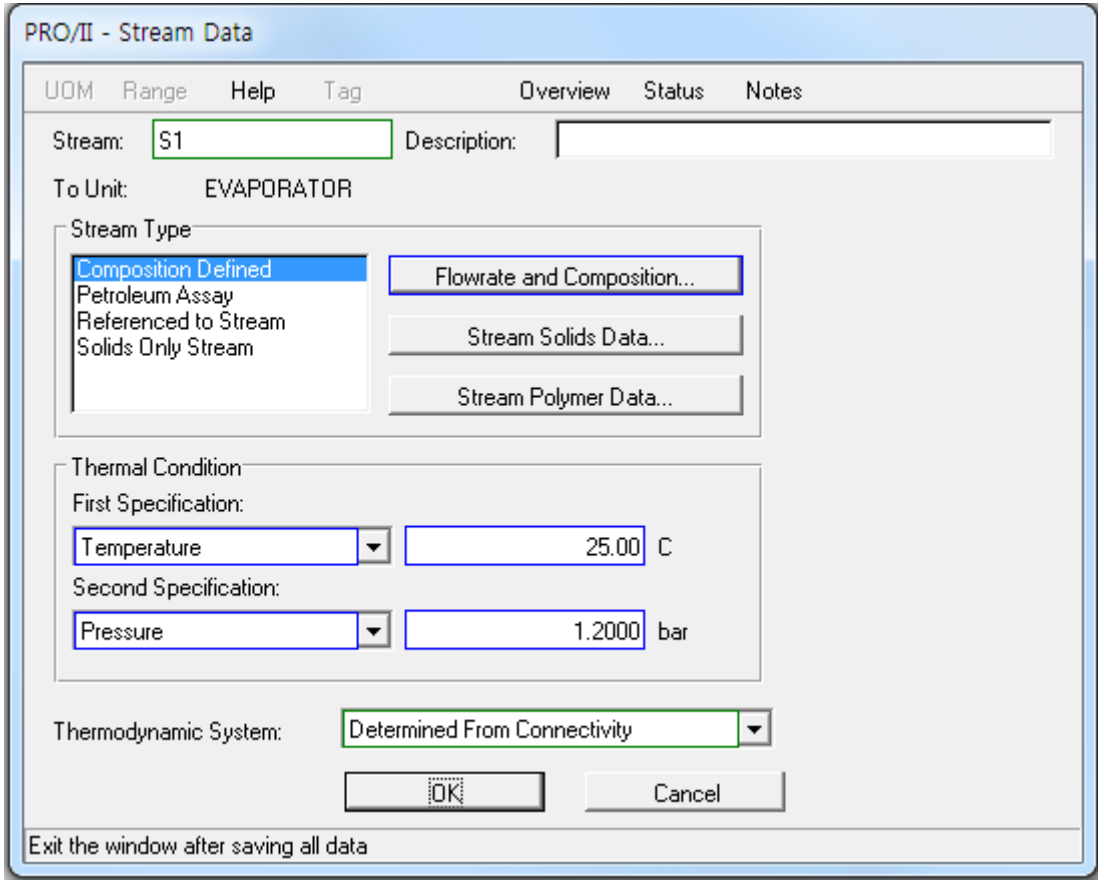
1.1143 bar

Step 4b: Refrigerant Flow Rate to the Evaporator: Controller

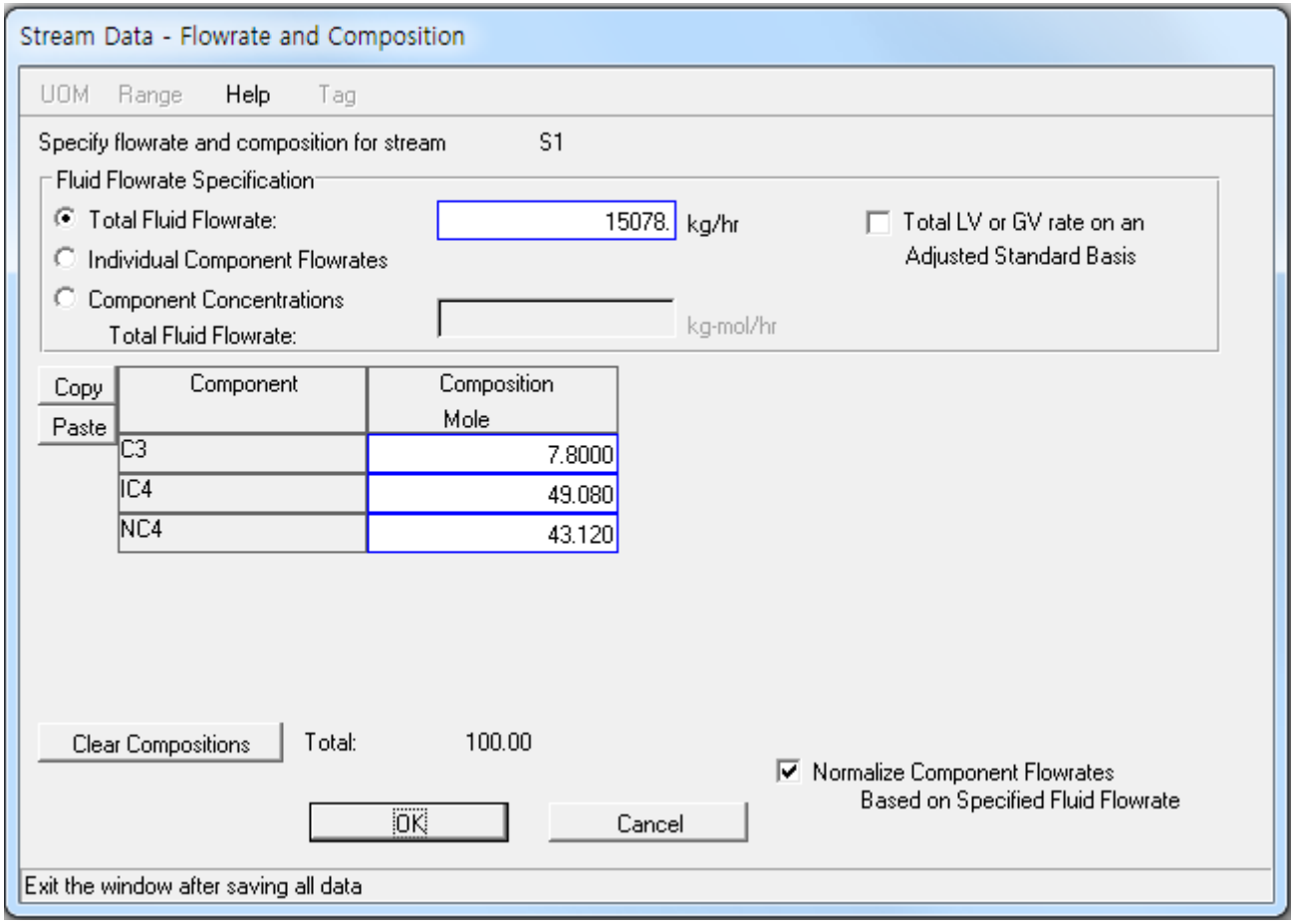


Step_04a_Refrigerant flowrate to the evaporator with controller.prz

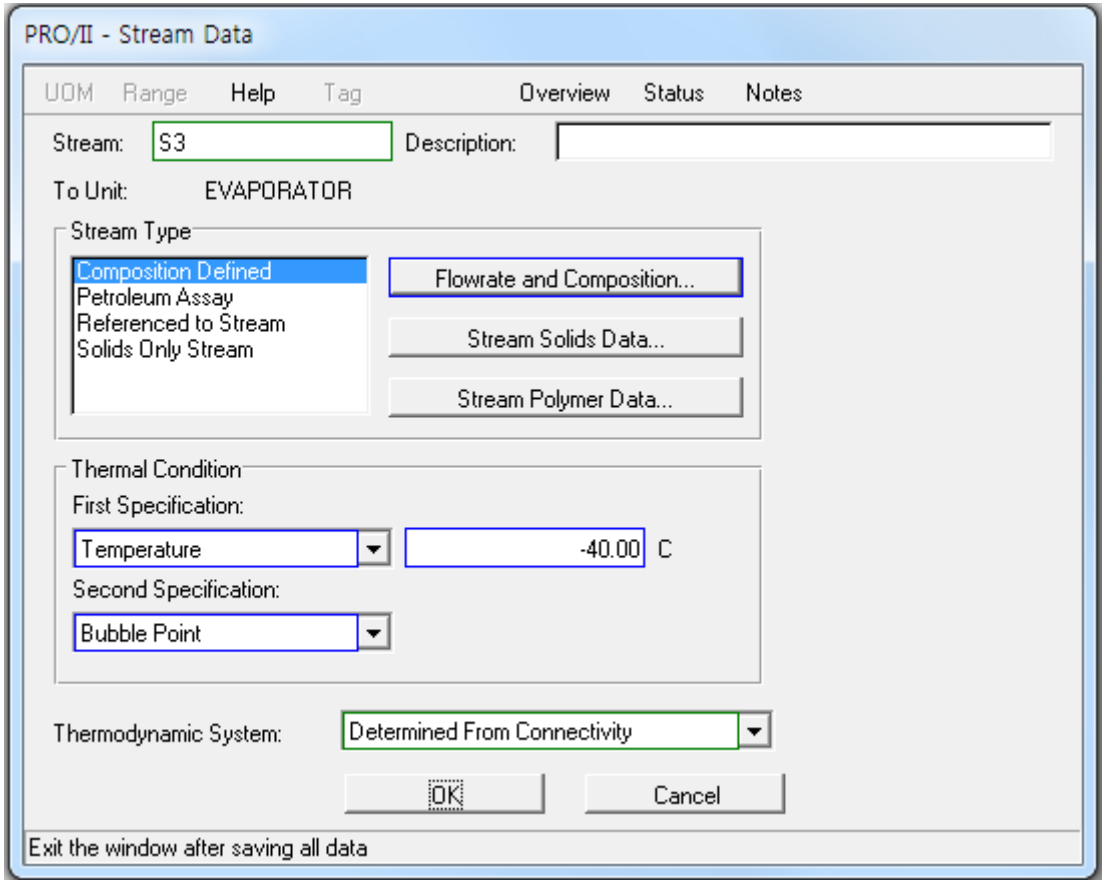
Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



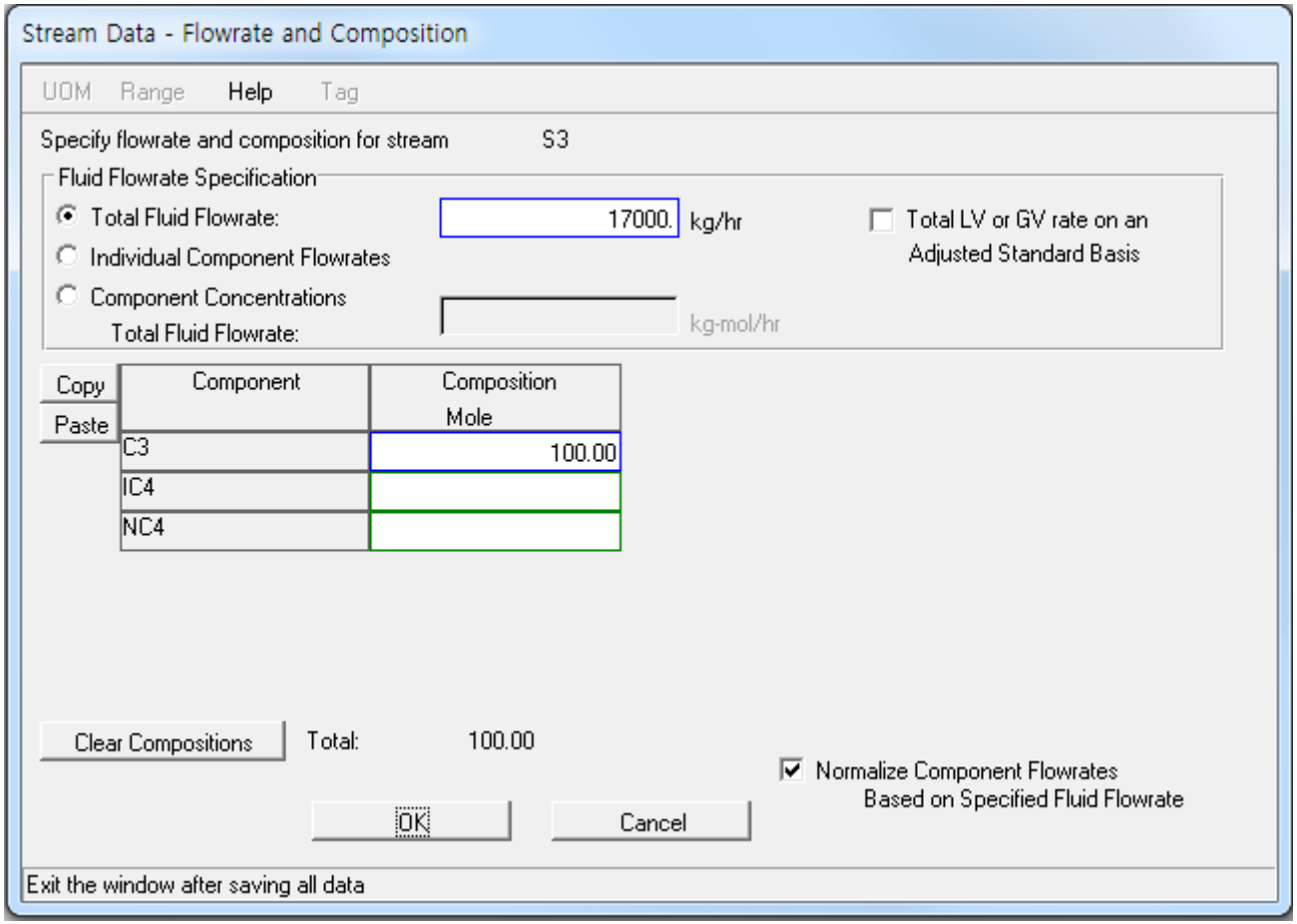
Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



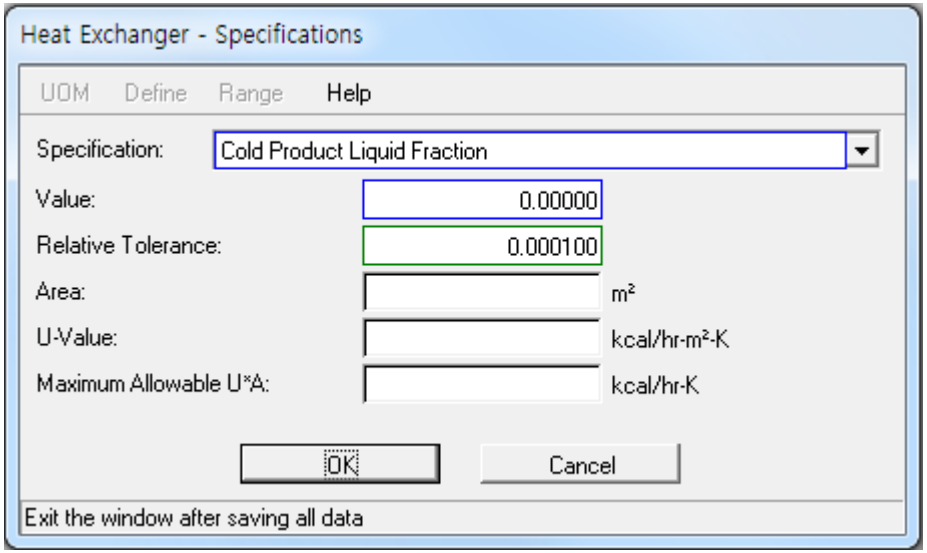
Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



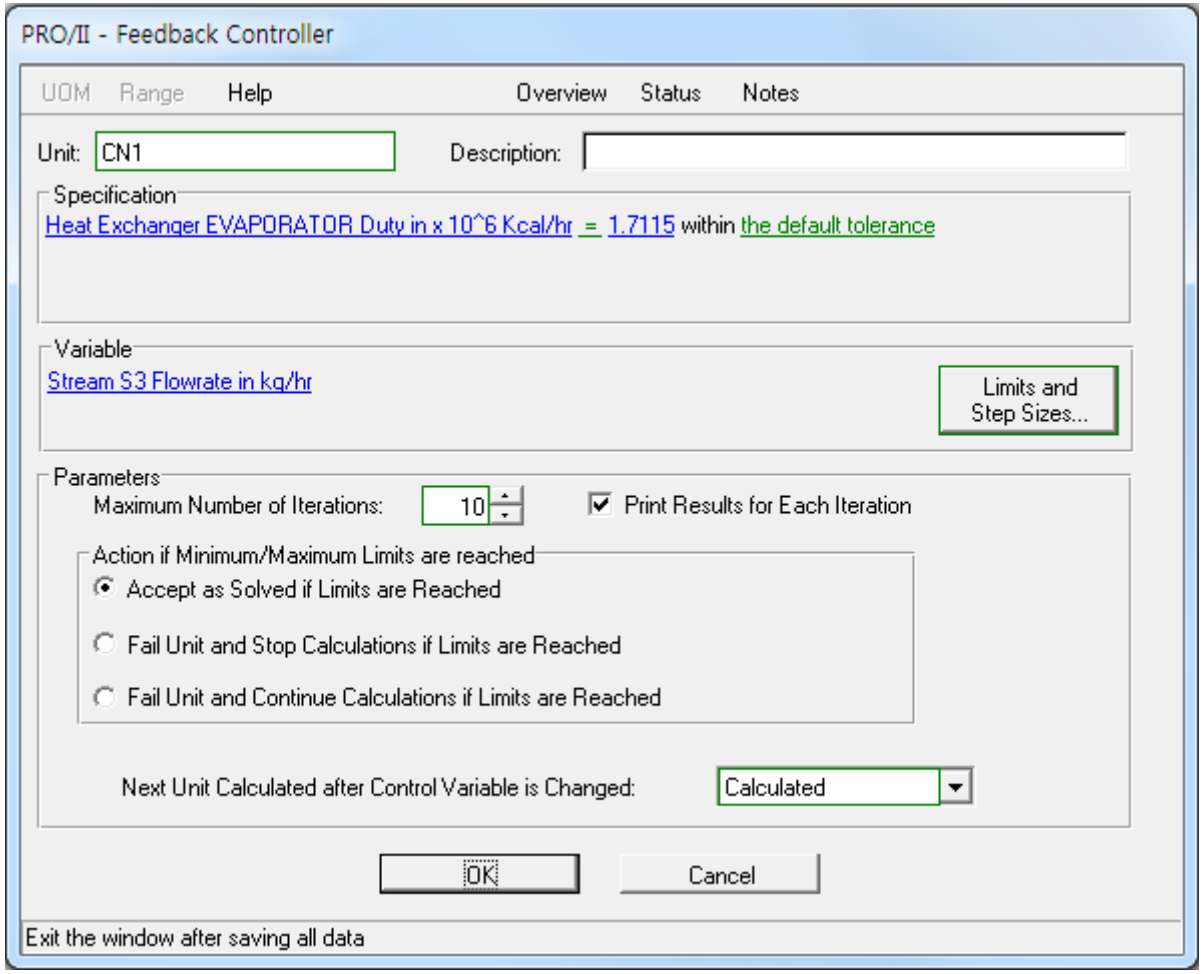
Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



Step 4b: Refrigerant Flow Rate to the Evaporator: Controller



Step 4b: Refrigerant Flow Rate to the Evaporator: Controller

OPERATING CONDITIONS

DUTY, M*KCAL/HR	**1.712**	
HOT SIDE CONDITIONS	INLET	OUTLET
FEED	S1	
TOTAL, KG-MOL/HR	264.390	264.390
K*KG/HR	15.078	15.078
CONDENSATION, KG-MOL/HR		264.390
TEMPERATURE, C	25.000	-30.000
PRESSURE, BAR	1.200	1.200
COLD SIDE CONDITIONS	INLET	OUTLET
FEED	S3	
VAPOR PRODUCT		S4
TOTAL, KG-MOL/HR	385.053	385.053
K*KG/HR	**16.979**	**16.979**
VAPORIZATION, KG-MOL/HR		385.053
TEMPERATURE, C	**-40.000**	**-40.000**
PRESSURE, BAR	**1.114**	**1.114**

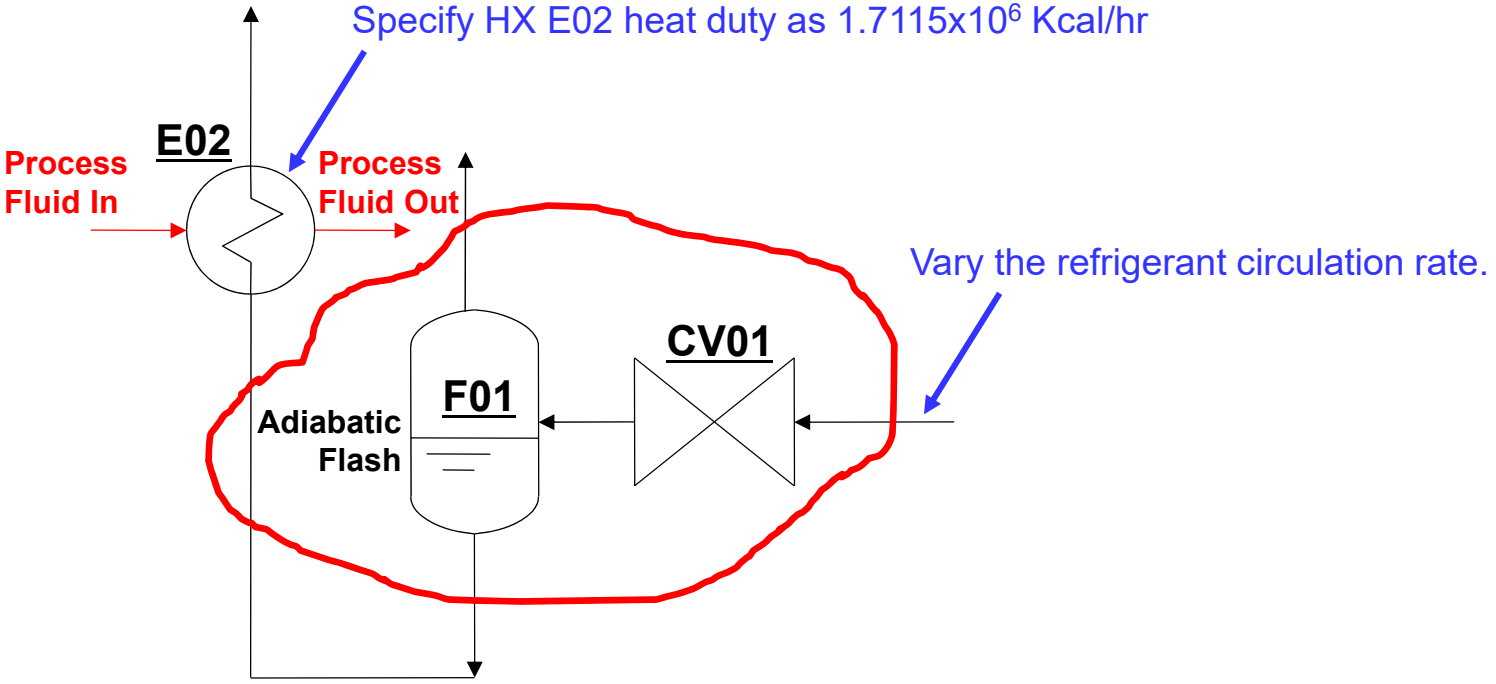
Step 4b: Refrigerant Flow Rate to the Evaporator: Controller

STREAM ID	S1	S2	S3	S4
NAME				
PHASE	VAPOR	LIQUID	LIQUID	VAPOR
THERMO ID	PR01	PR01	PR01	PR01
FLUID RATES, KG/HR				
1 C3	909.3783	909.3783	16979.4860	16979.4860
2 IC4	7542.2557	7542.2557	0.0000	0.0000
3 NC4	6626.3660	6626.3660	0.0000	0.0000
TOTAL RATE, KG/HR	15078.0000	15078.0000	**16979.4860**	**16979.4860**
TEMPERATURE, C	25.0000	-29.9966	**-40.0000**	**-40.0000**
PRESSURE, BAR	1.2000	1.2000	**1.1143**	**1.1143**
ENTHALPY, M*KCAL/HR	1.5001	-0.2114	-0.3596	1.3519
MOLECULAR WEIGHT	57.0293	57.0293	44.0965	44.0965
WEIGHT FRAC VAPOR	1.0000	0.0000	0.0000	1.0000
WEIGHT FRAC LIQUID	0.0000	1.0000	1.0000	0.0000

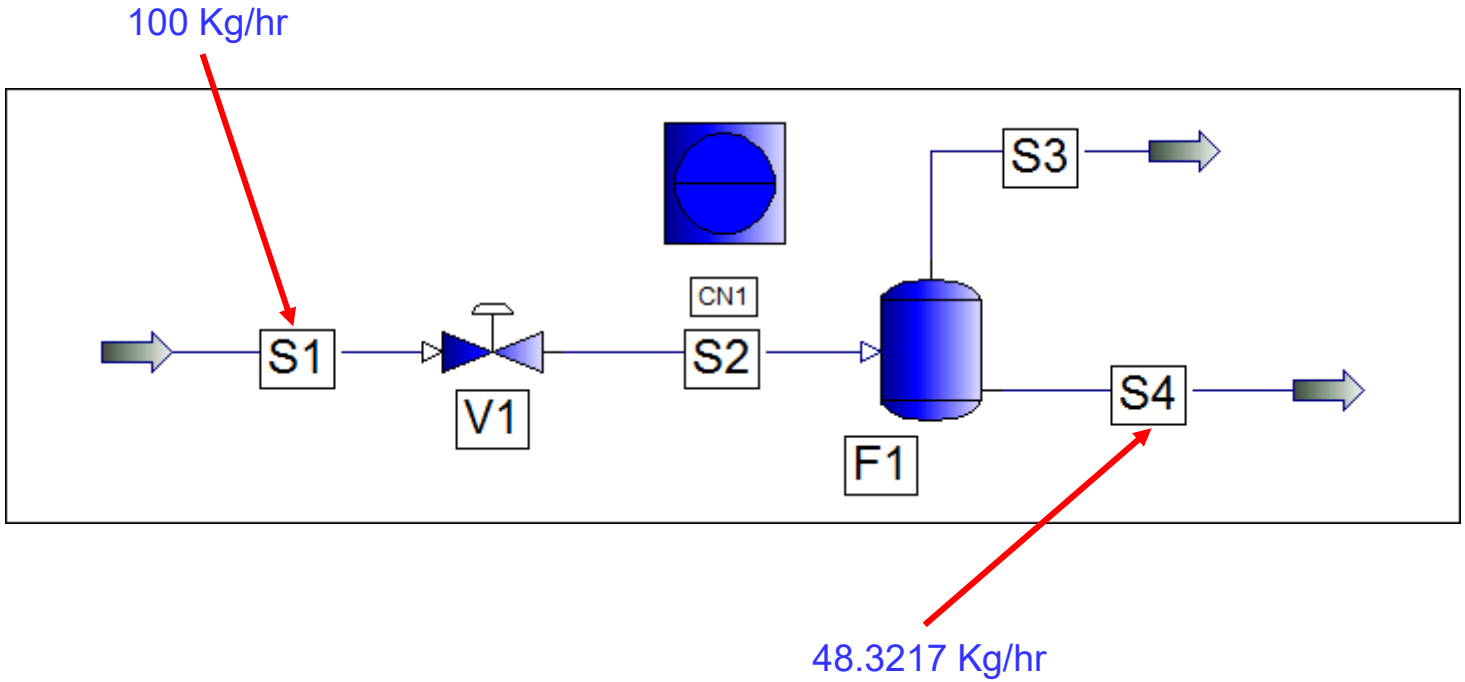
5 Estimation of the Total Refrigerant Circulation Rate

Step 5: Total Refrigerant Flow Rate

- Total refrigerant circulation rate
  - A: Use proportional relation with valve and flash module
  - B: Specify heat exchanger In principle, expansion valve outlet pressure is equal to the dew point pressure of propane at -40^{o}C using Peng-Robinson equation of state.



Step 5a: Total Refrigerant Flow Rate

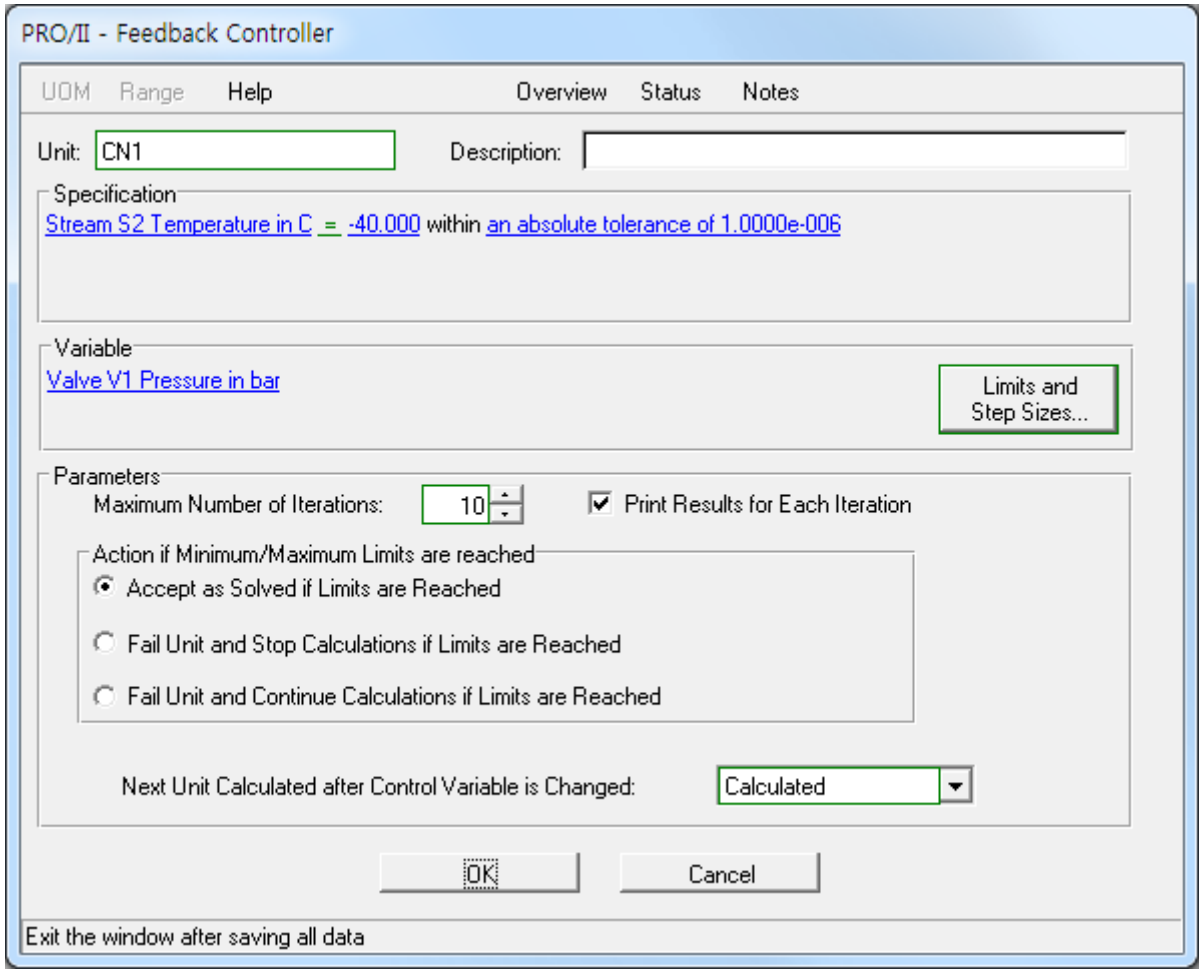


$$100 : 48.3217 = x : 16{,}979.486$$

$$x = 35{,}138.4285$$

Step_05a_Total refrigerant circulation rate.prz

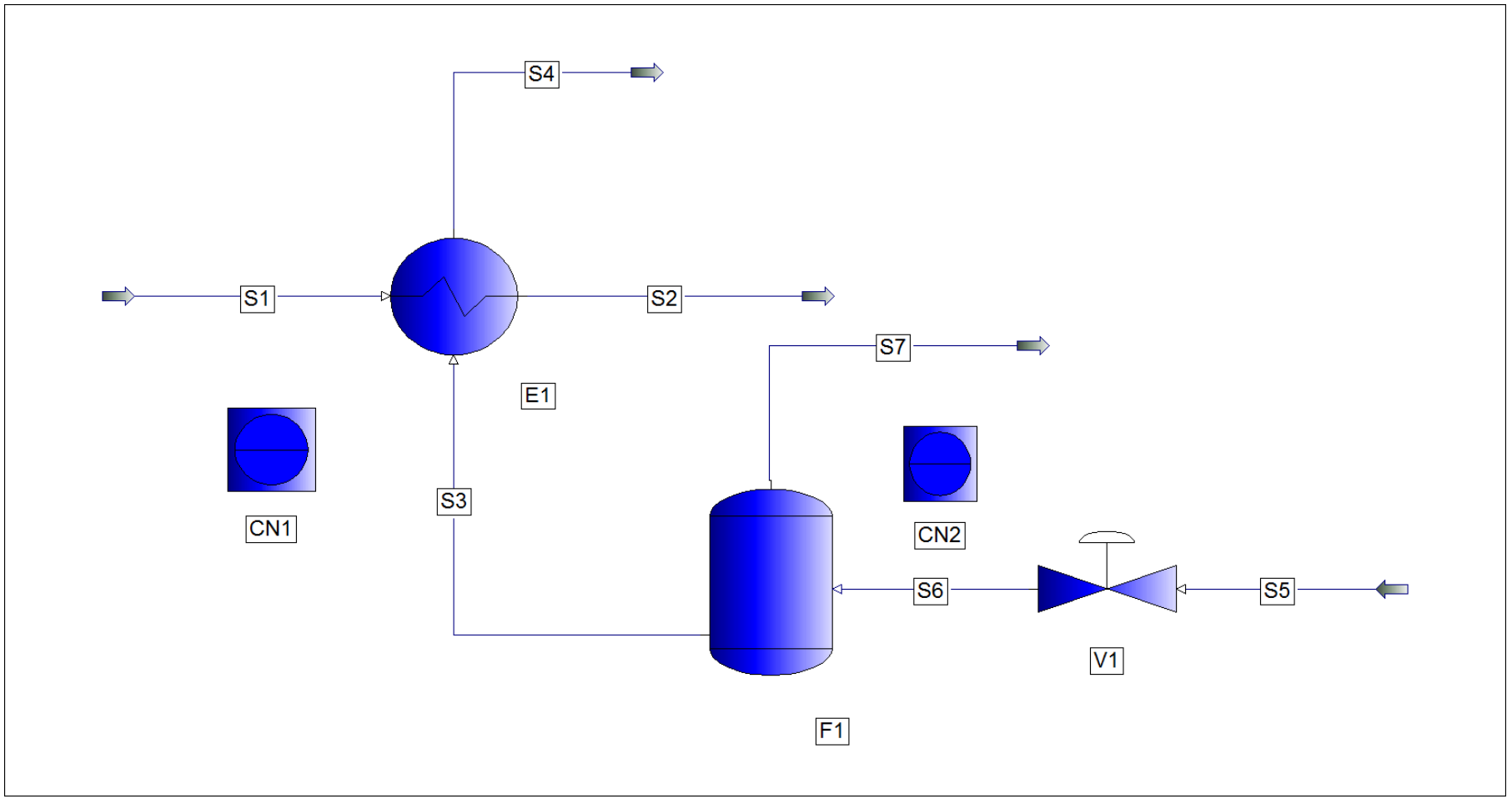
Step 5a: Total Refrigerant Flow Rate



Step 5a: Total Refrigerant Flow Rate

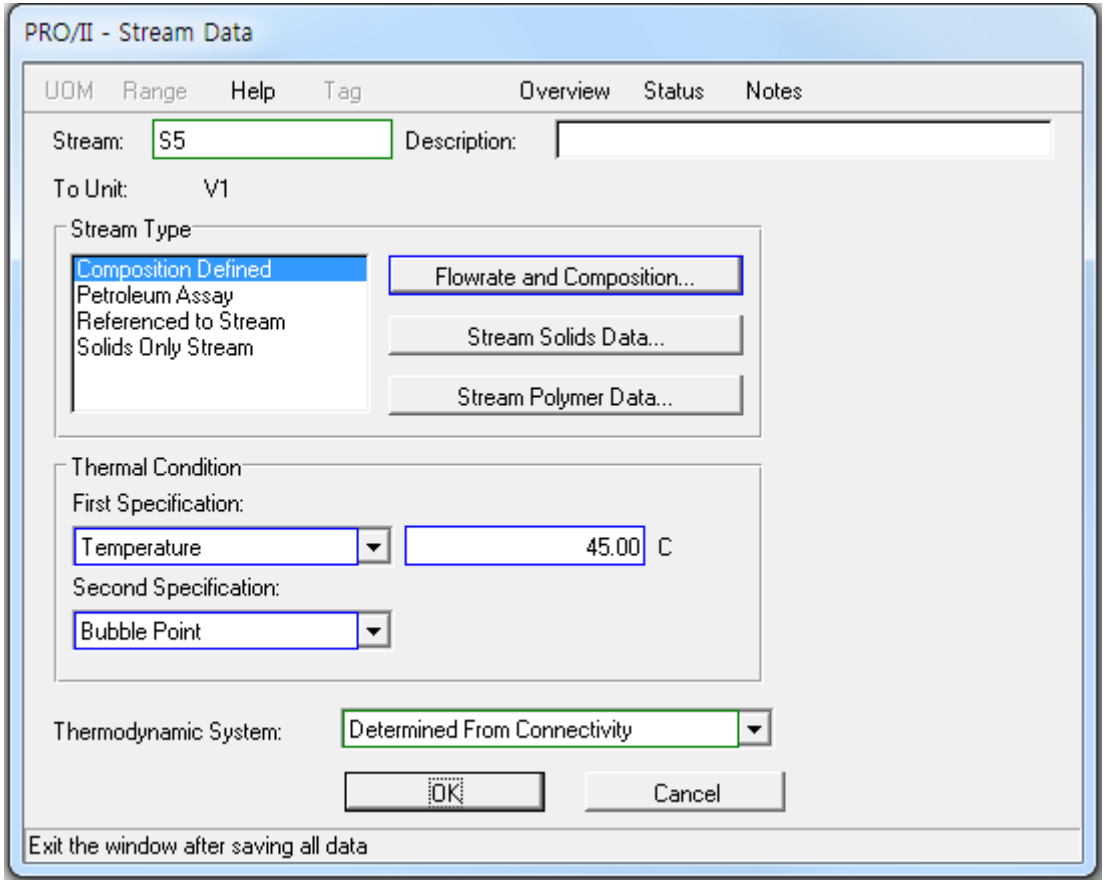
STREAM ID	S1	S2	S3	S4
NAME				
PHASE	LIQUID	MIXED	VAPOR	LIQUID
THERMO ID	PR01	PR01	PR01	PR01
FLUID RATES, KG/HR				
1 C3	100.0000	100.0000	51.6783	48.3217
2 IC4	0.0000	0.0000	0.0000	0.0000
3 NC4	0.0000	0.0000	0.0000	0.0000
TOTAL RATE, KG/HR	100.0000	100.0000	51.6783	**48.3217**
TEMPERATURE, C	45.0000	-40.0000	**-40.0000**	**-40.0000**
PRESSURE, BAR	15.3845	1.1143	1.1143	1.1143
ENTHALPY, M*KCAL/HR	3.0915E-03	3.0915E-03	4.1148E-03	-1.0232E-03
MOLECULAR WEIGHT	44.0965	44.0965	44.0965	44.0965
WEIGHT FRAC VAPOR	0.0000	0.5168	1.0000	0.0000
WEIGHT FRAC LIQUID	1.0000	0.4832	0.0000	1.0000

Step 5b: Total Refrigerant Flow Rate: Controllers

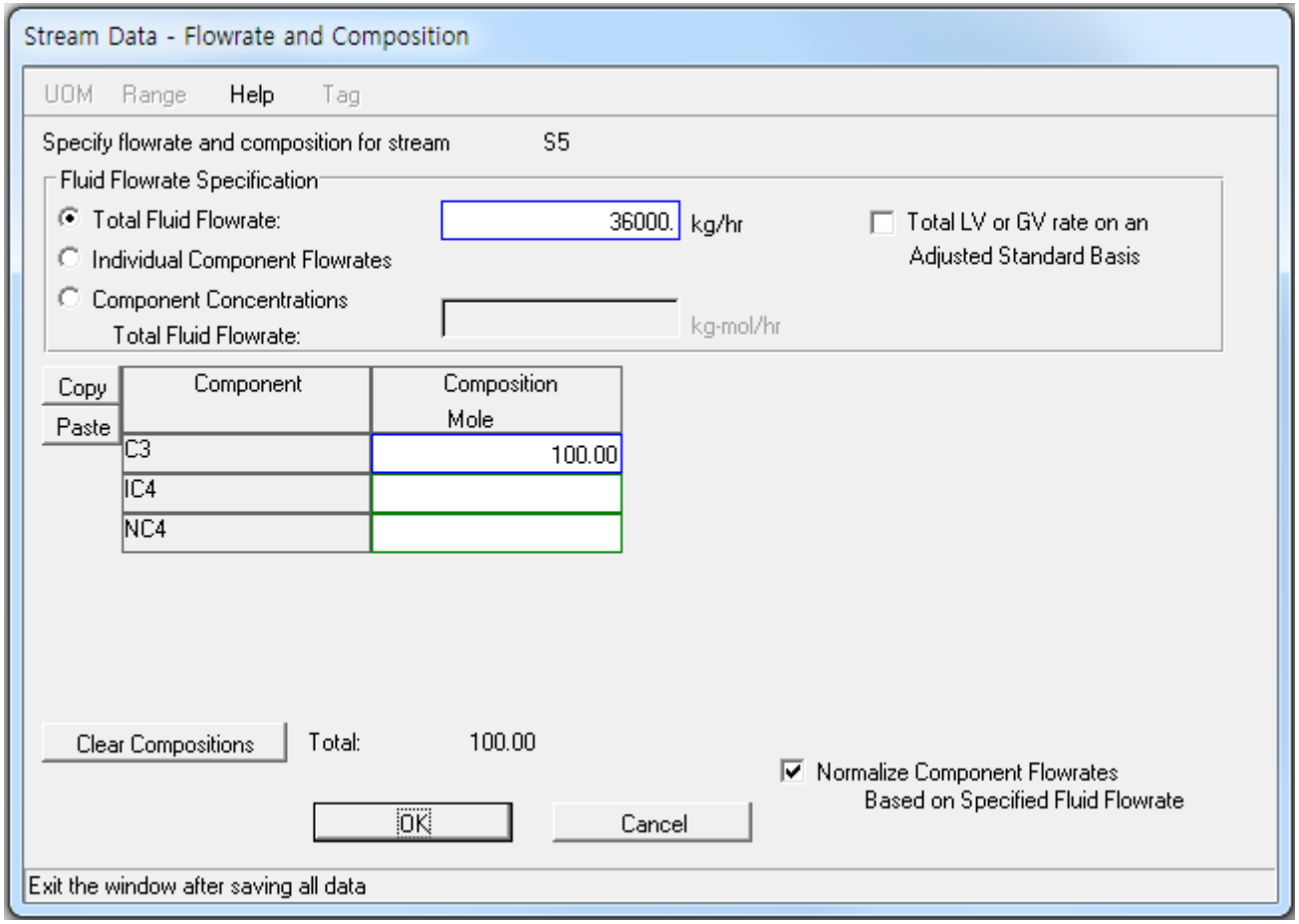


Step_05b_Total refrigerant circulation rate with controller.prz

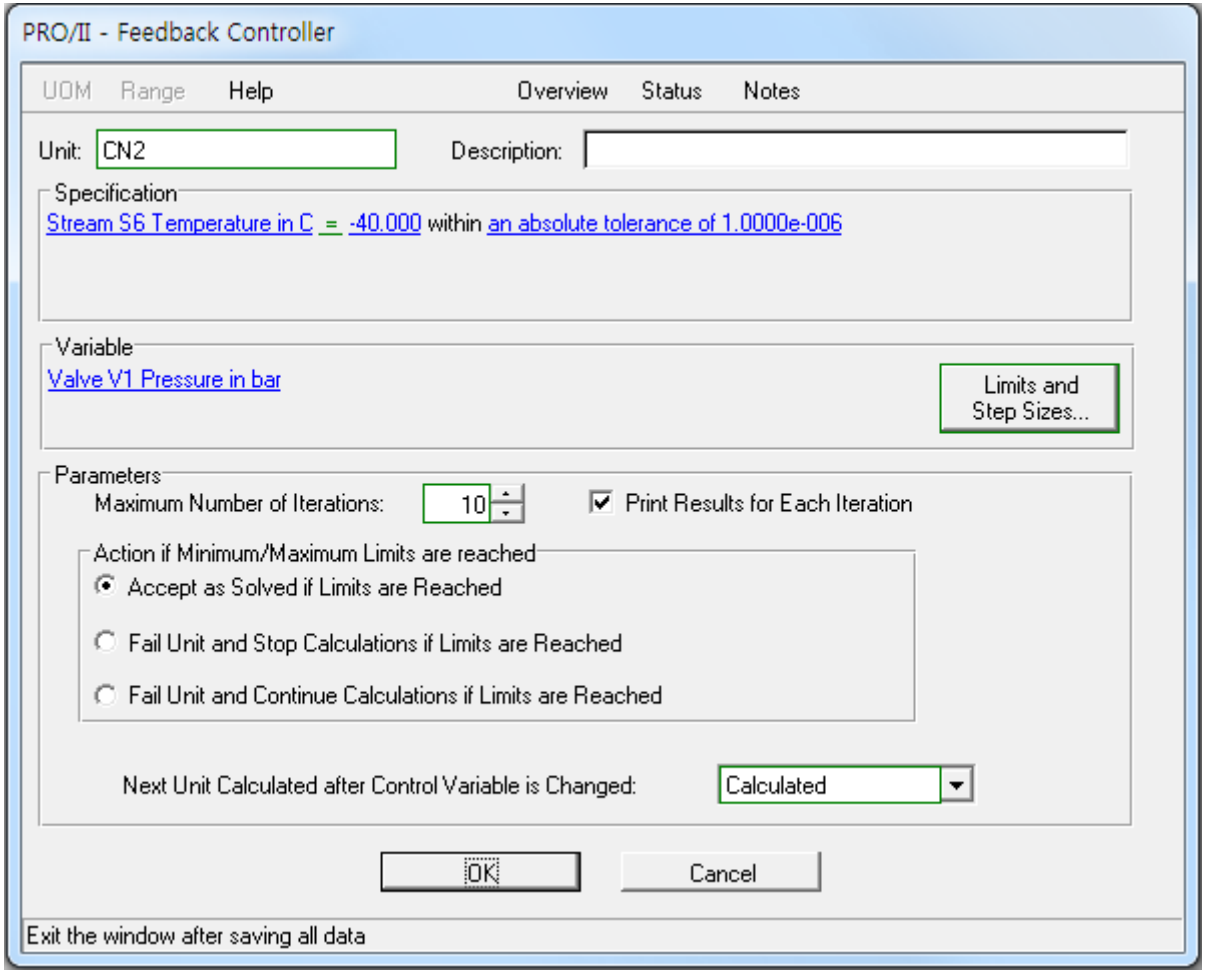
Step 5b: Total Refrigerant Flow Rate: Controllers



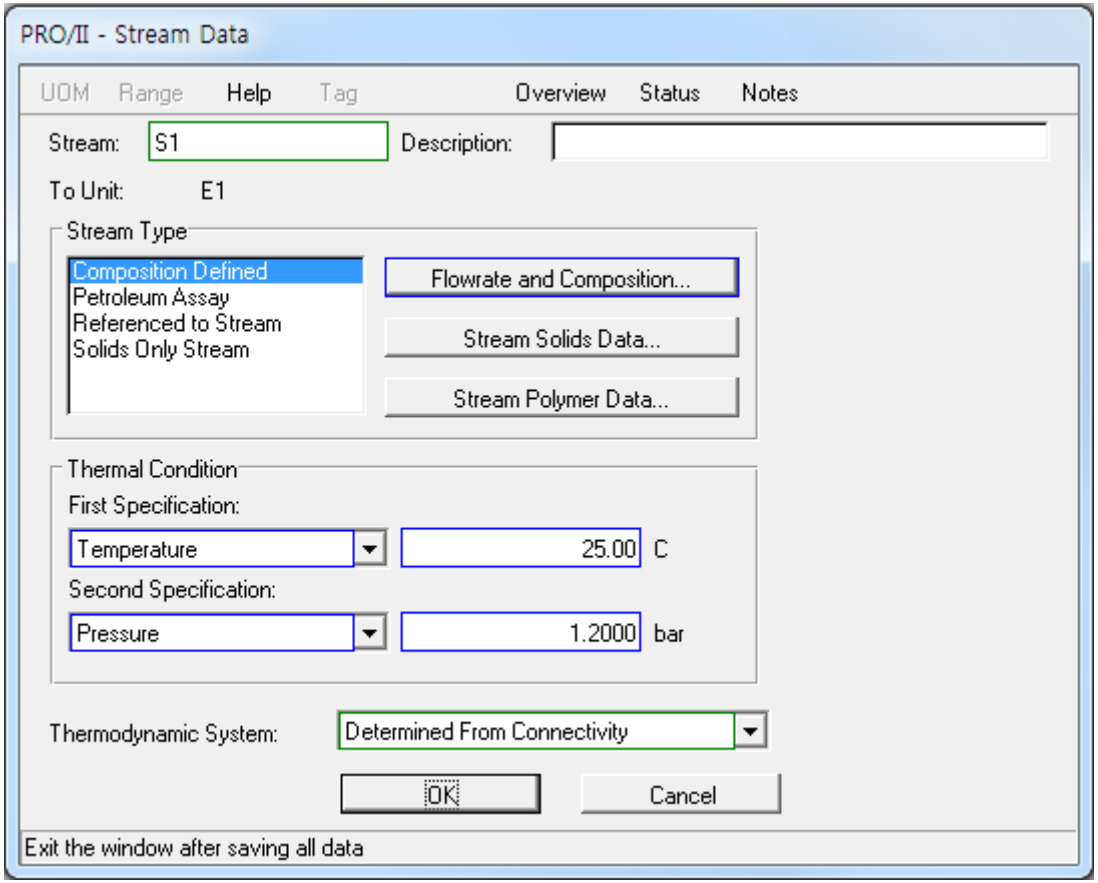
Step 5b: Total Refrigerant Flow Rate: Controllers



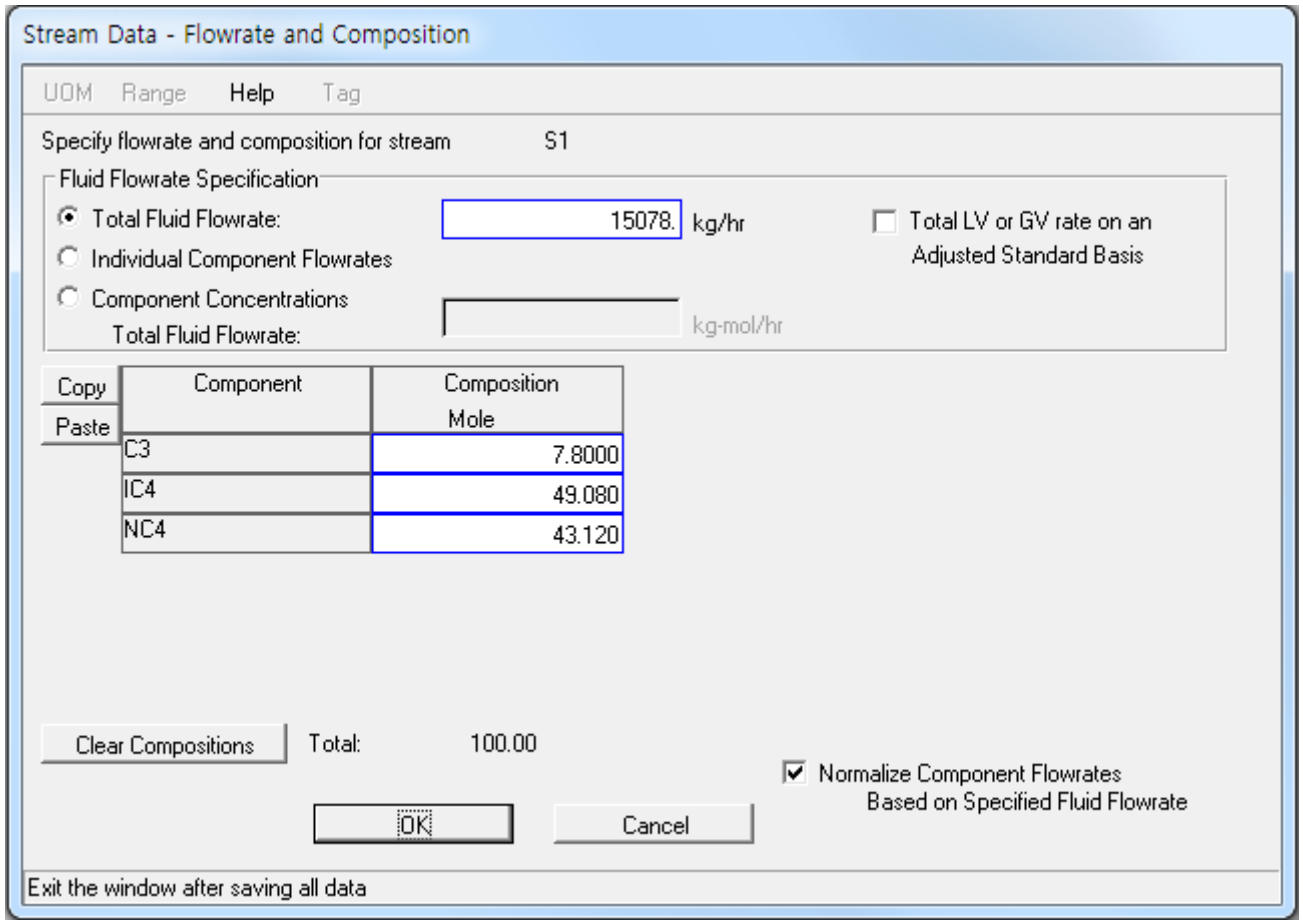
Step 5b: Total Refrigerant Flow Rate: Controllers



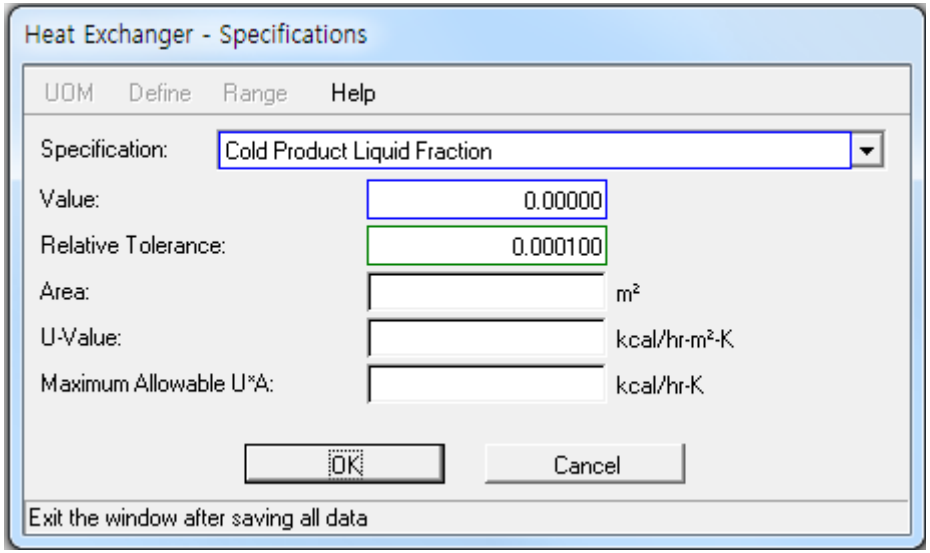
Step 5b: Total Refrigerant Flow Rate: Controllers



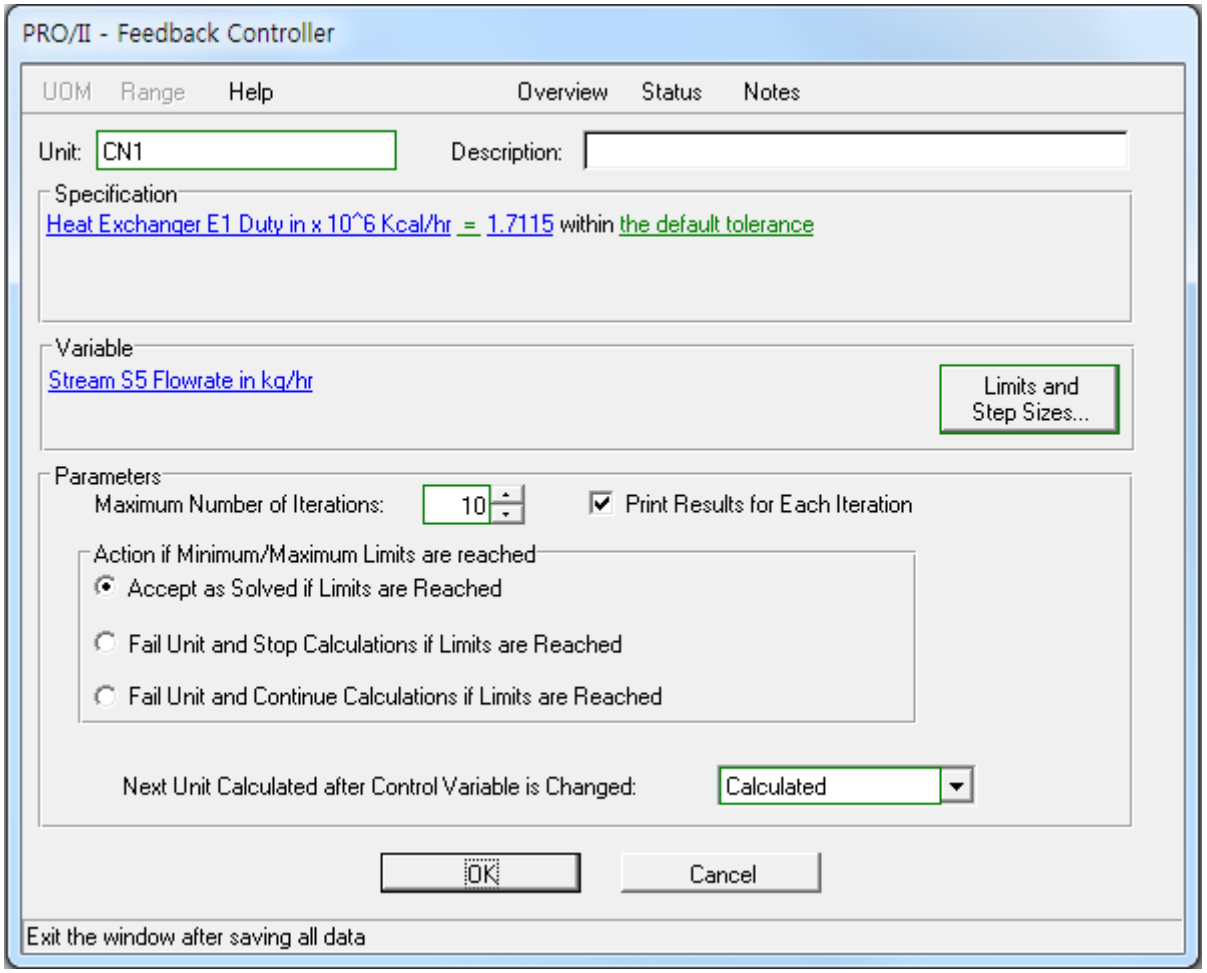
Step 5b: Total Refrigerant Flow Rate: Controllers



Step 5b: Total Refrigerant Flow Rate: Controllers

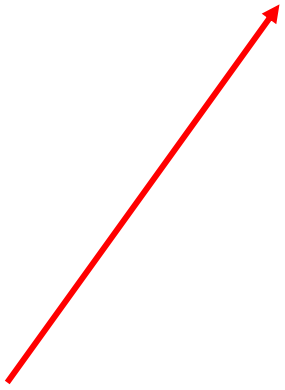


Step 5b: Total Refrigerant Flow Rate: Controllers



Step 5b: Total Refrigerant Flow Rate: Controllers

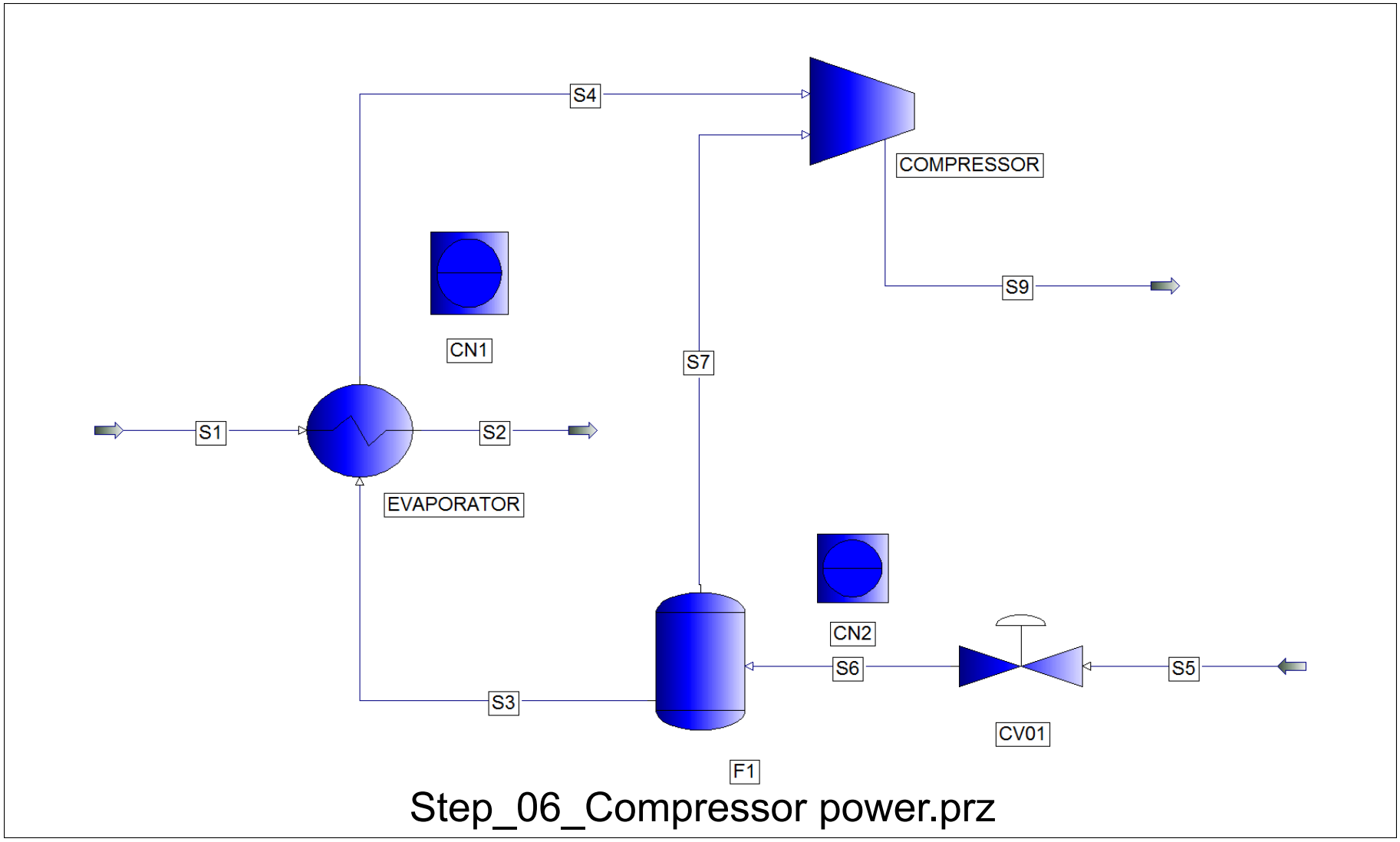
STREAM ID	**S5**	S6	S7
NAME			
PHASE	LIQUID	MIXED	VAPOR
THERMO ID	PR01	PR01	PR01
FLUID RATES, KG/HR			
1 C3	35138.3627	35138.3627	18158.9207
2 IC4	0.0000	0.0000	0.0000
3 NC4	0.0000	0.0000	0.0000
TOTAL RATE, KG/HR	**35138.3627**	35138.3627	18158.9207
TEMPERATURE, C	45.0000	-40.0000	-40.0000
PRESSURE, BAR	15.3845	1.1143	1.1143
ENTHALPY, M*KCAL/HR	1.0863	1.0863	1.4459
MOLECULAR WEIGHT	44.0965	44.0965	44.0965
WEIGHT FRAC VAPOR	0.0000	0.5168	1.0000
WEIGHT FRAC LIQUID	1.0000	0.4832	0.0000



A: 35,138.4285 Kg/hr

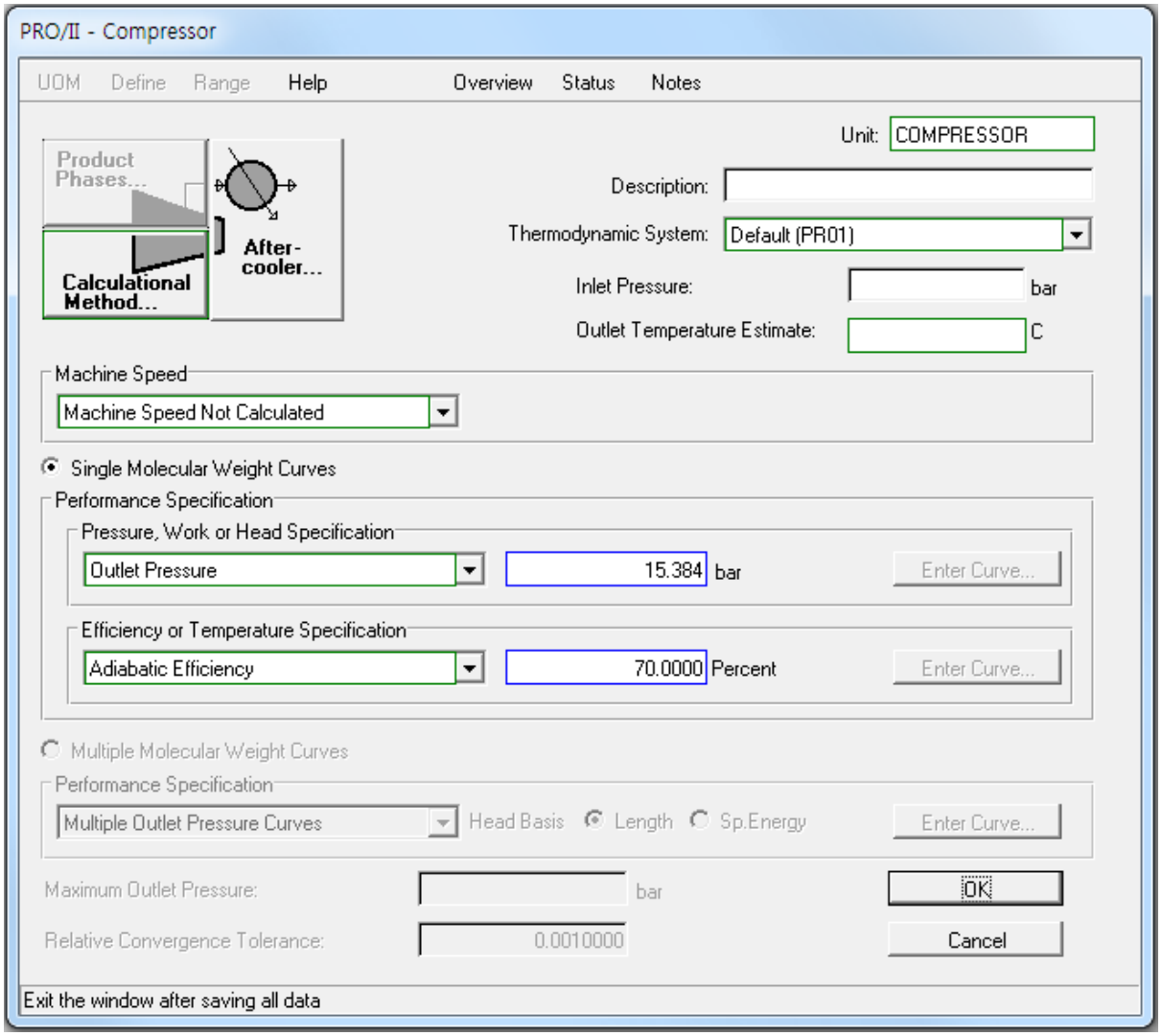
6 Compressor Power (Adiabatic efficiency: 70%), Compressor Discharge Temperature

Step 6: Compressor Power & Discharge Temperature



Step_06_Compressor power.prz

Step 6: Compressor Power & Discharge Temperature



Step 6: Compressor Power & Discharge Temperature

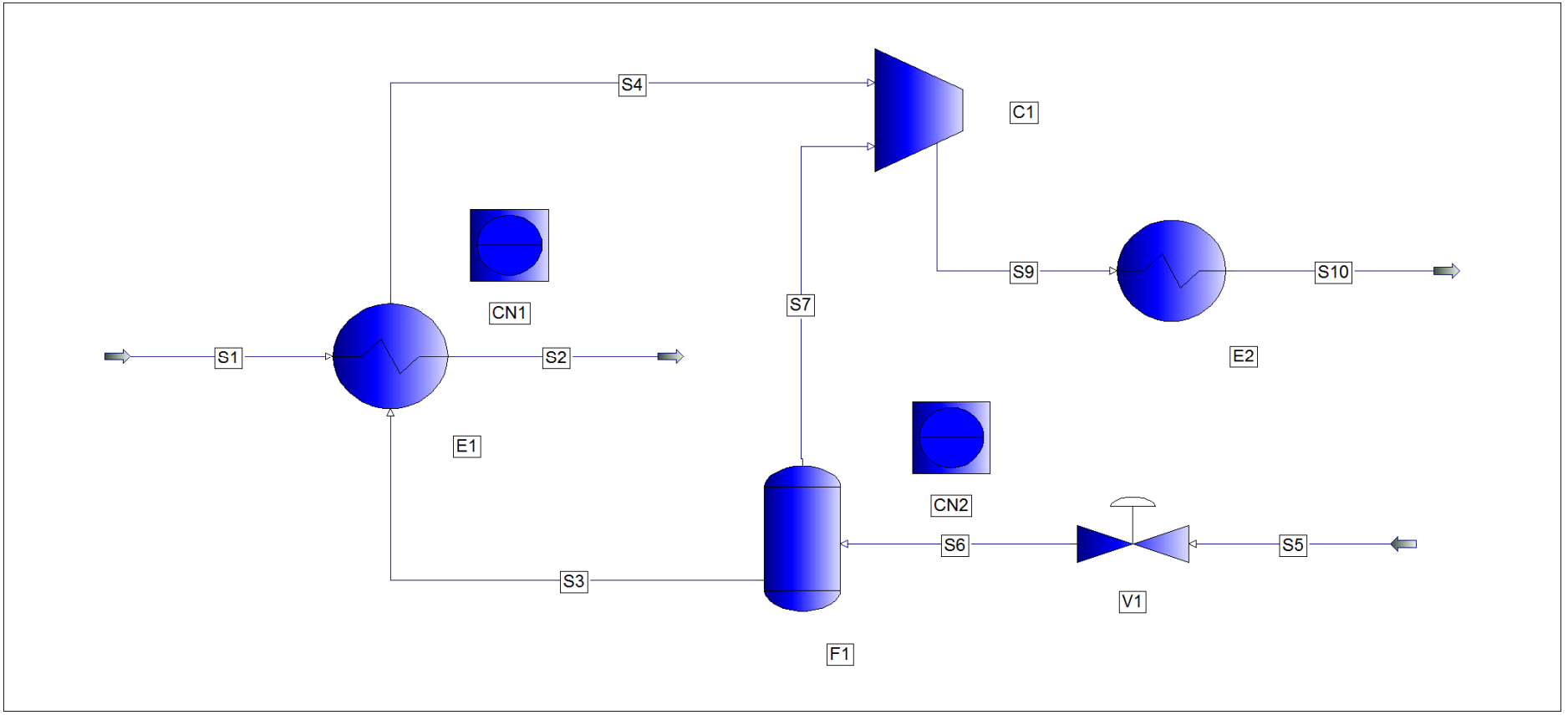
UNIT 5, 'COMPRESSOR'

OPERATING CONDITIONS

	INLET	ISENTROPIC	OUTLET
TEMPERATURE, C	**-40.00**	**59.87**	**84.90**
PRESSURE, BAR	**1.11**	**15.38**	**15.38**
ENTHALPY, M*KCAL/HR	2.7978	3.8411	4.2882
ADIABATIC EFF, PERCENT			**70.0000**
POLYTROPIC EFF, PERCENT			74.9913
ISENTROPIC COEFFICIENT, K			1.0611
POLYTROPIC COEFFICIENT, N			1.1214
ASME "F" FACTOR			1.0349
HEAD, M			
ADIABATIC			12675.70
POLYTROPIC			13579.53
ACTUAL			18108.14
WORK, KW			
THEORETICAL			1213.31
POLYTROPIC			1299.82
ACTUAL			**1733.30**

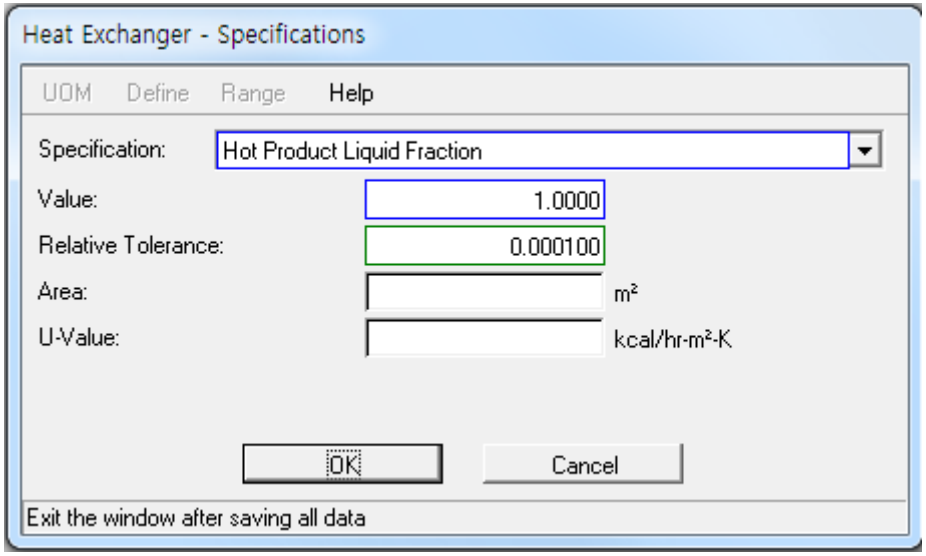
7 Estimation of the Condenser Heat Duty & Cooling Water Consumptions

Step 7: Condenser Heat Duty

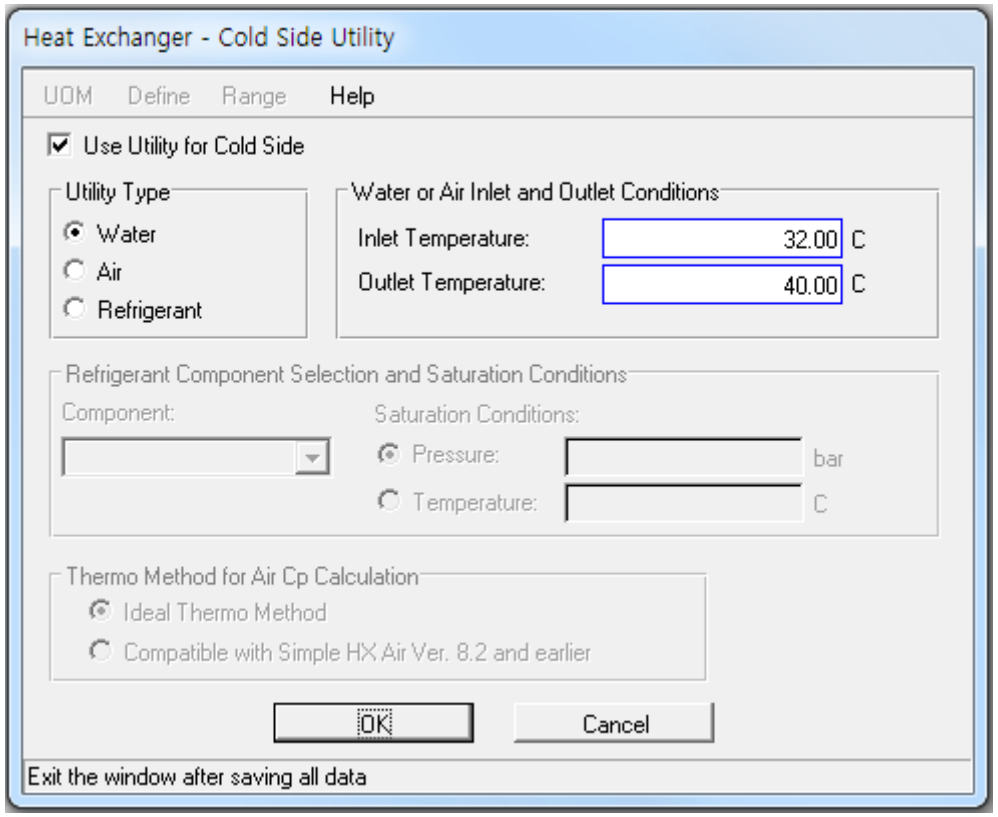


Step_07_Condenser duty.prz

Step 7: Condenser Heat Duty



Step 7: Cooling Water Consumptions



Step 7: Cooling Water Consumptions

OPERATING CONDITIONS

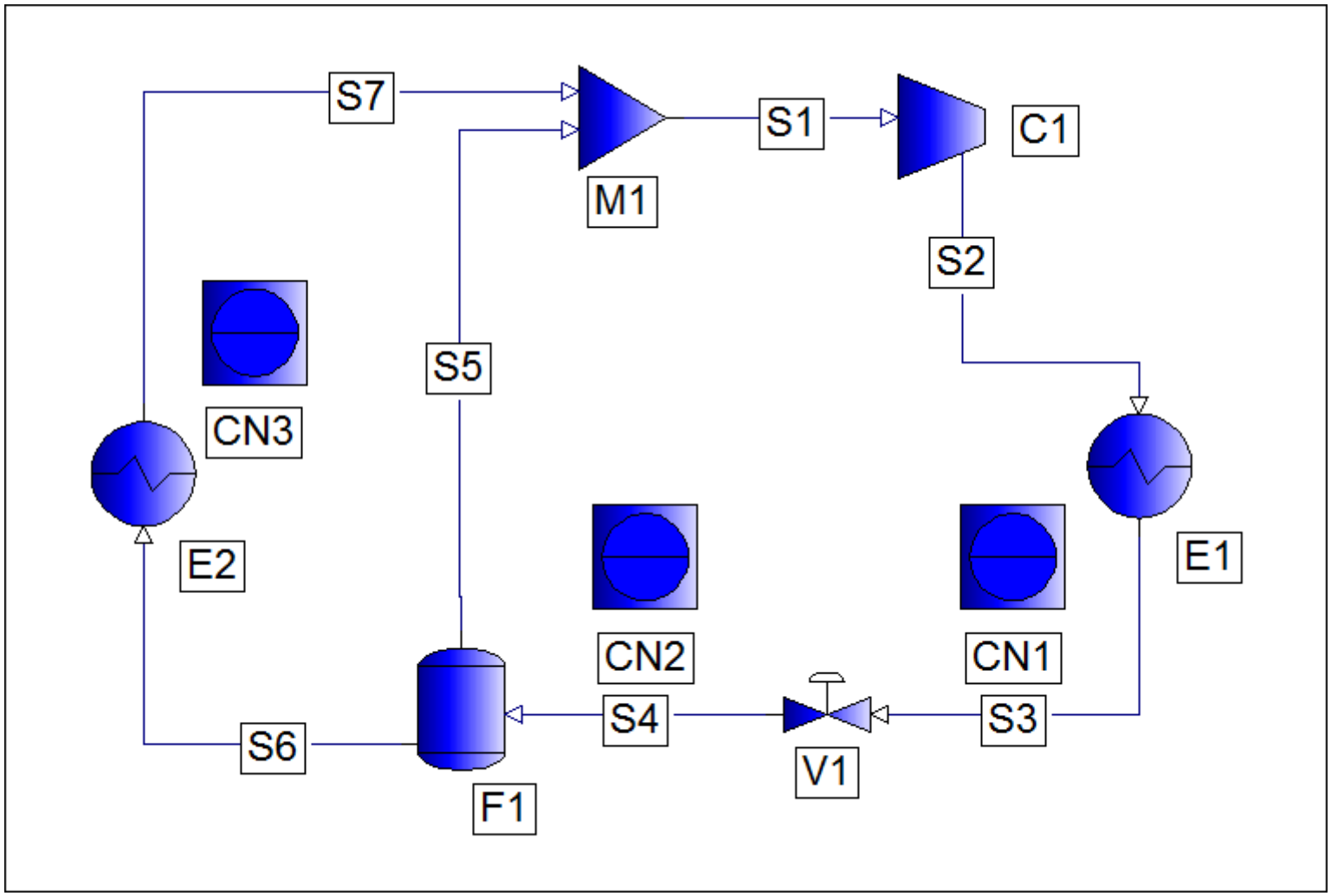
DUTY, M*KCAL/HR	**3.202**	
LMTD, C	25.737	

HOT SIDE CONDITIONS	INLET	OUTLET
FEED	S9	
LIQUID PRODUCT		S10
VAPOR, KG-MOL/HR	796.851	
K*KG/HR	35.138	
CP, KCAL/KG-C	0.514	
LIQUID, KG-MOL/HR		796.851
K*KG/HR		35.138
CP, KCAL/KG-C		0.769
TOTAL, KG-MOL/HR	796.851	796.851
K*KG/HR	35.138	35.138
CONDENSATION, KG-MOL/HR		796.851
TEMPERATURE, C	84.901	45.000
PRESSURE, BAR	15.384	15.384

COLD SIDE CONDITIONS	INLET	OUTLET
COOLING WATER, KG/HR	**400237.921**	**400237.921**
TEMPERATURE, C	**32.000**	**40.000**

8 Overall Refrigeration Cycle Using Pure Propane

Step 8: Overall Refrigeration Cycle



Step_09_Overall refrigeration cycle.prz

Step 8: Overall Refrigeration Cycle

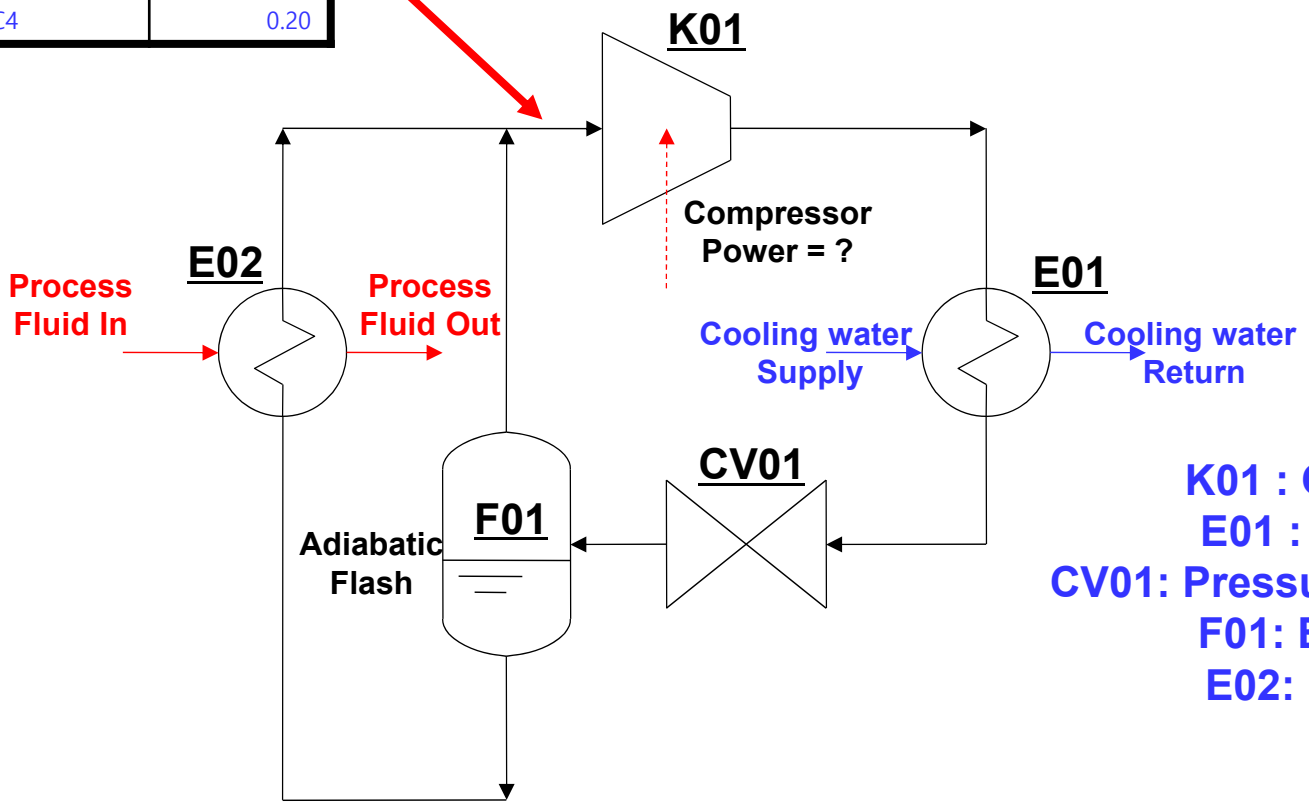
Step	Item	Stepwise Calculation	Overall Simulation
1	Evaporator heat duty (10^6 Kcal/hr)	1.7115	1.7115
2	Compressor discharge pressure (bar)	15.3845 (15.385) (15.384)	15.3845
3	Expansion valve outlet pressure (bar)	1.1143 (1.114) (1.114)	1.114
4	Refrigerant mass flow rate to the evaporator (kg/hr)	16,946.501 (16,979.486)	16,979.4872
5	Total refrigerant circulation rate (kg/hr)	35,138.4285 (35,138.3627)	35,138.4597
6	Compressor power (kW) & compressor outlet stream temperature (°C)	1733.30, 84.90	1,733.31, 84.901
7	Condenser heat duty (10^6 Kcal/hr)	3.202	3.2019
8	Cooling water consumptions (Ton/hr)	400.0	400.2

9 Pure Refrigerant vs. Mixed Refrigerants

Step 9: Pure Refrigerant vs. Mixed Refrigerants

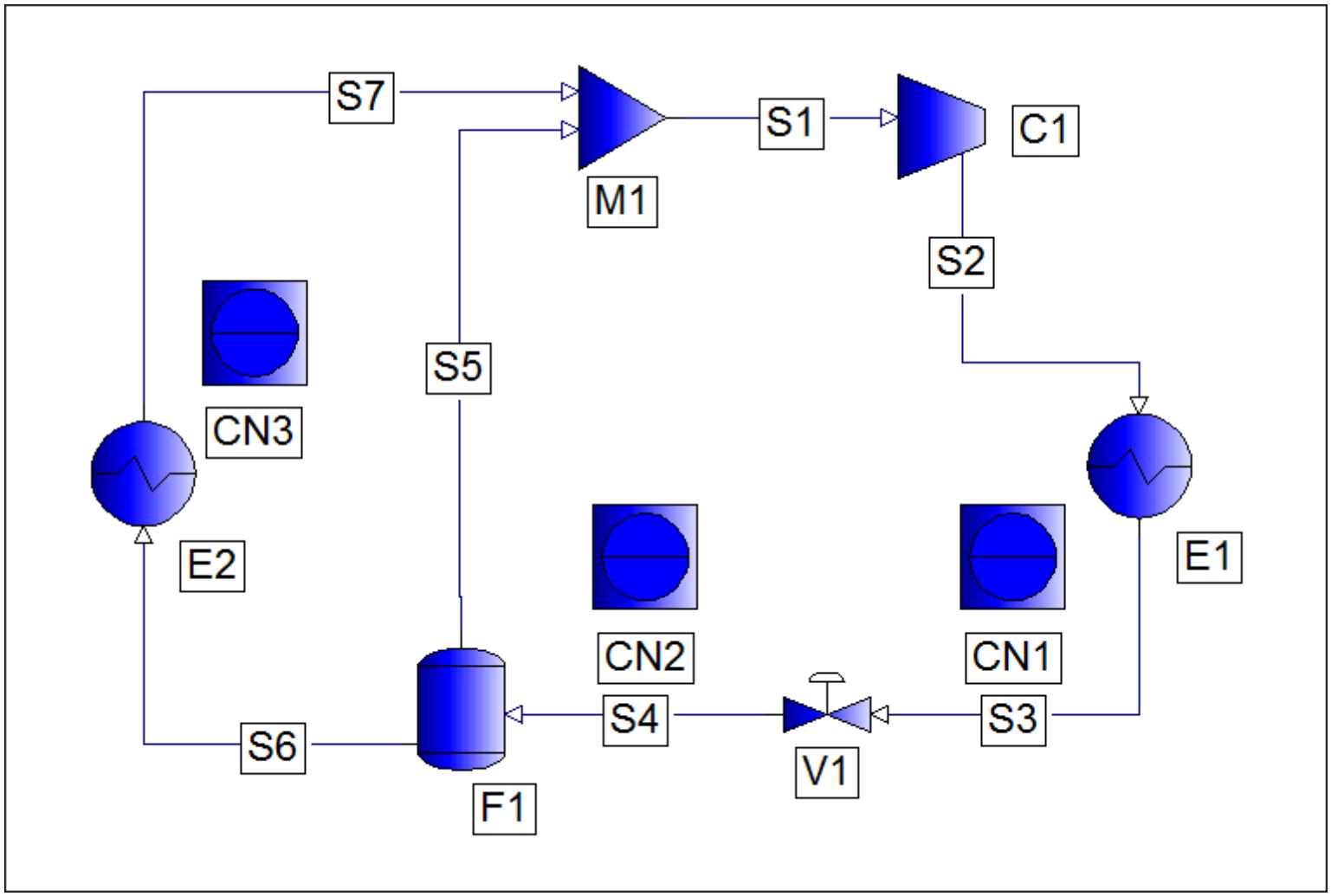
Component	Mole%
C2	0.50
C3	98.5
IC4	0.80
NC4	0.20

실제로는 약간의 혼합냉매임
따라서 순수성분 냉매일 때는 증발기 후단에서 온도 변화가 없으나 혼합냉매일 경우에는 약간의 온도증가가 발생함



K01 : Compressor
E01 : Condenser
CV01: Pressure Let-down Valve
F01: Economizer
E02: Evaporator

Step 9: Pure Refrigerant vs. Mixed Refrigerants



Step_10_Overall refrigeration cycle using mixed refrigeratns .prz

Step 9: Pure Refrigerant vs. Mixed Refrigerants

Step	Item	Stepwise Calculation	Overall Simulation (Pure)	Overall Simulation (Mixed)
1	Evaporator heat duty (10^6 Kcal/hr)	1.7115	1.7115	1.7115
2	Compressor discharge pressure (bar)	15.3845 (15.385) (15.384)	15.3845	15.434
3	Expansion valve outlet pressure (bar)	1.1143 (1.114) (1.114)	1.114	1.108
4	Refrigerant mass flow rate to the evaporator (kg/hr)	16,946.501 (16,979.486)	16,979.4872	16,939.8899
5	Total refrigerant circulation rate (kg/hr)	35,138.4285 (35,138.3627)	35,138.4597	35,026.3962
6	Compressor power (kW) & compressor outlet stream temperature (^oC)	1733.30, 84.90	1,733.31, 84.901	1,736.0957, 85.7399
7	Condenser heat duty (10^6 Kcal/hr)	3.202	3.2019	3.2044
8	Cooling water consumptions (Ton/hr)	400.0	400.2	400.6

10 다른 종류의 냉동 사이클에 대한 예시

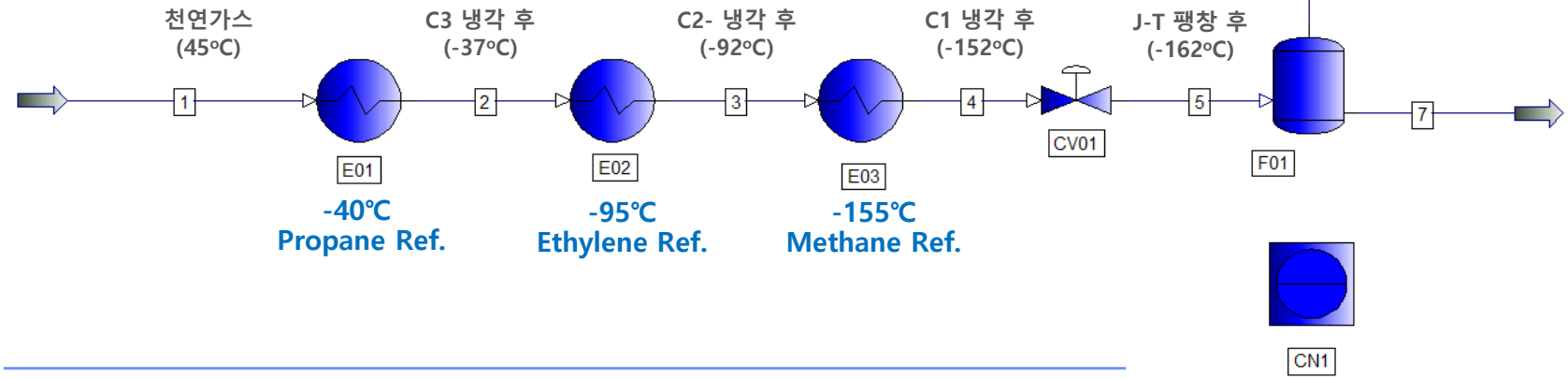
천연가스 냉각을 위한 조건:

E01/E02/E03

Pressure drop : 0.5 bar

CN1

Spec : stream7 Temp -162 ℃
Variable : CV01 Pressure

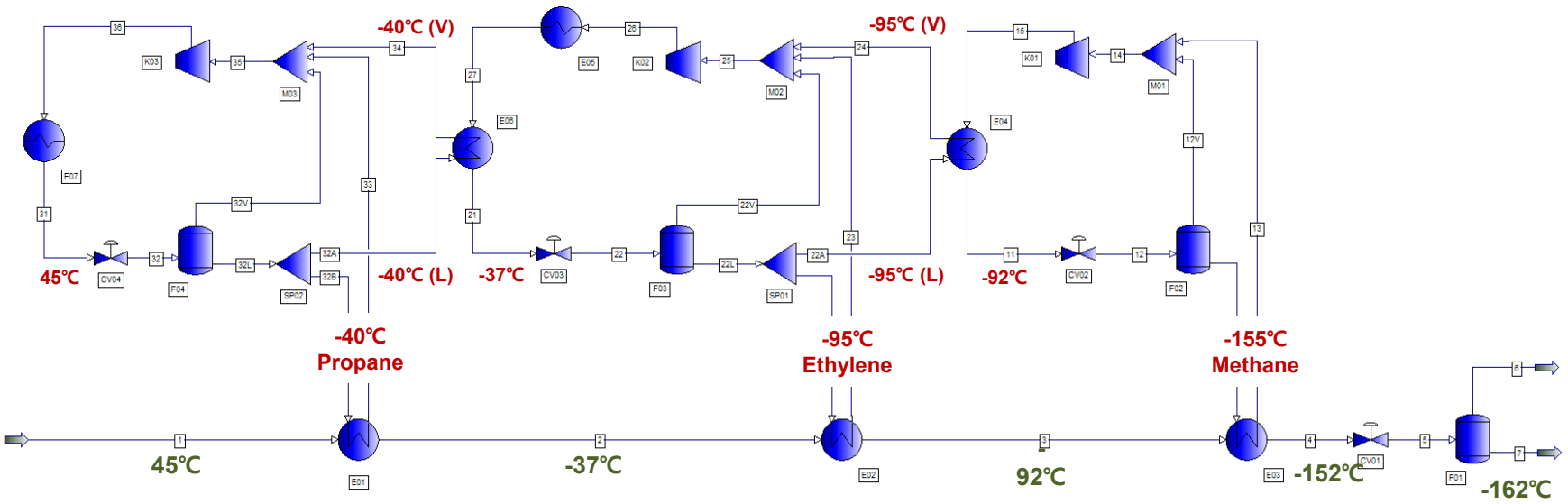


Hx name	E01	E02	E03
Duty (10^6 Kcal/hr)	34.0145	58.5202	32.2301
Refrigerant Flow (kg/hr)	337,452	526,206	270,075

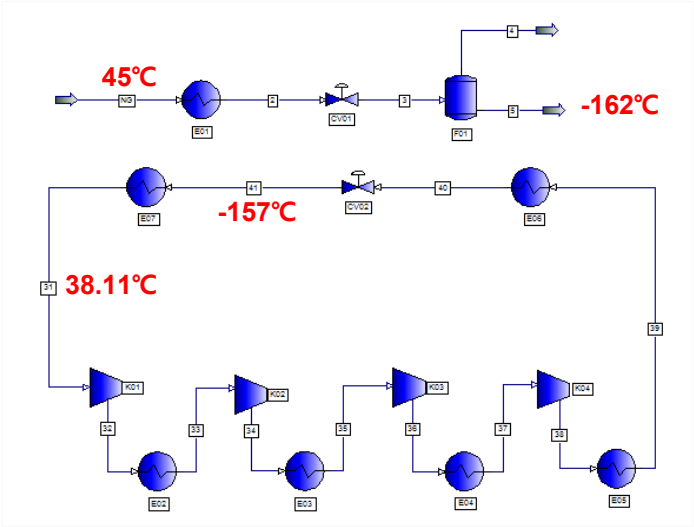
Stream name	1	2	3	4
Temperature	**45℃**	-37℃	-92℃	**-152℃**
Pressure	53 bar	52.5 bar	52 bar	51.5 bar

증발기로 들어가는 냉매의 유량을 알 수 있다.
이것을 이용하여 각 냉동사이클의 초기냉매 유량을 구한다.

Cascade 냉동:


-40℃ (V)
-95℃ (V)
45℃
-40℃ (L)
-37℃
-95℃ (L)
-92℃
-40℃
Propane
-95℃
Ethylene
-155℃
Methane
45℃
-37℃
92℃
-152℃
-162℃

SMR 냉동:



SMR Composition

Component	Mole %
Nitrogen	7.14
Methane	11.91
Ethane	9.52
Propane	71.43
Total Flow (Kg/hr)	**4.2E+06**

SMR input Condition

Stream 31	Value
Temperature (℃)	38.11
Pressure (bar)	1.3

Cascade vs. SMR 냉동:

Cascade

Component	Compressor	Actual Work
C1	K01	65,915
C2-	K02	114,073
C3	K03	262,446
Total Actual work (kW)		**442,434**

LNG	Flowrate (kg/hr)
Stream5	577,310

Actual Work
0.7700 kW/(kg/hr LNG)

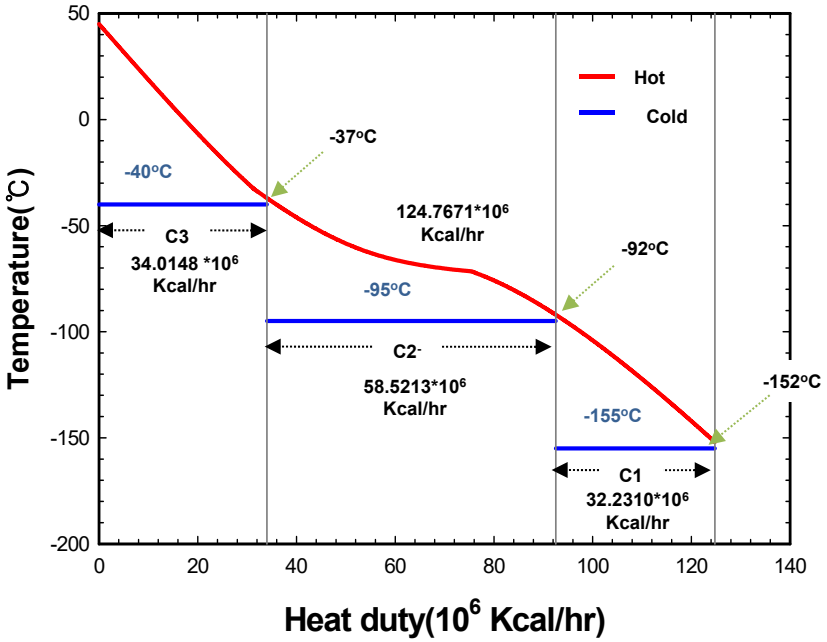
SMR

Component	Compressor	Actual Work
MR (C1, C2,C3, N2)	K01	99,255
	K02	98,265
	K03	94,661
	K04	86,503
Total Actual work (kW)		**378,684**

LNG	Flowrate (kg/hr)
Stream5	577,157

Actual Work
0.6561 kW/(kg/hr LNG)

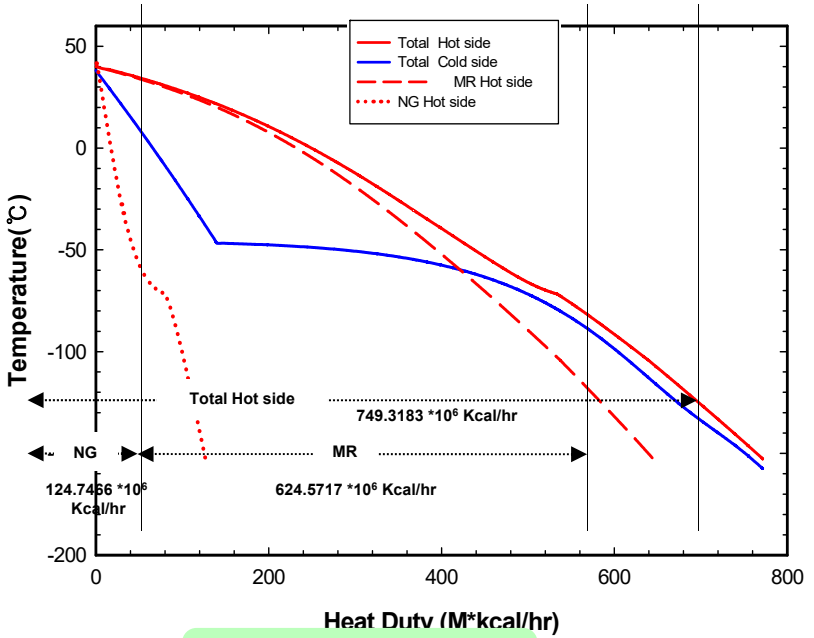
Cascade & SMR Heating Curve 비교:



Cascade Process

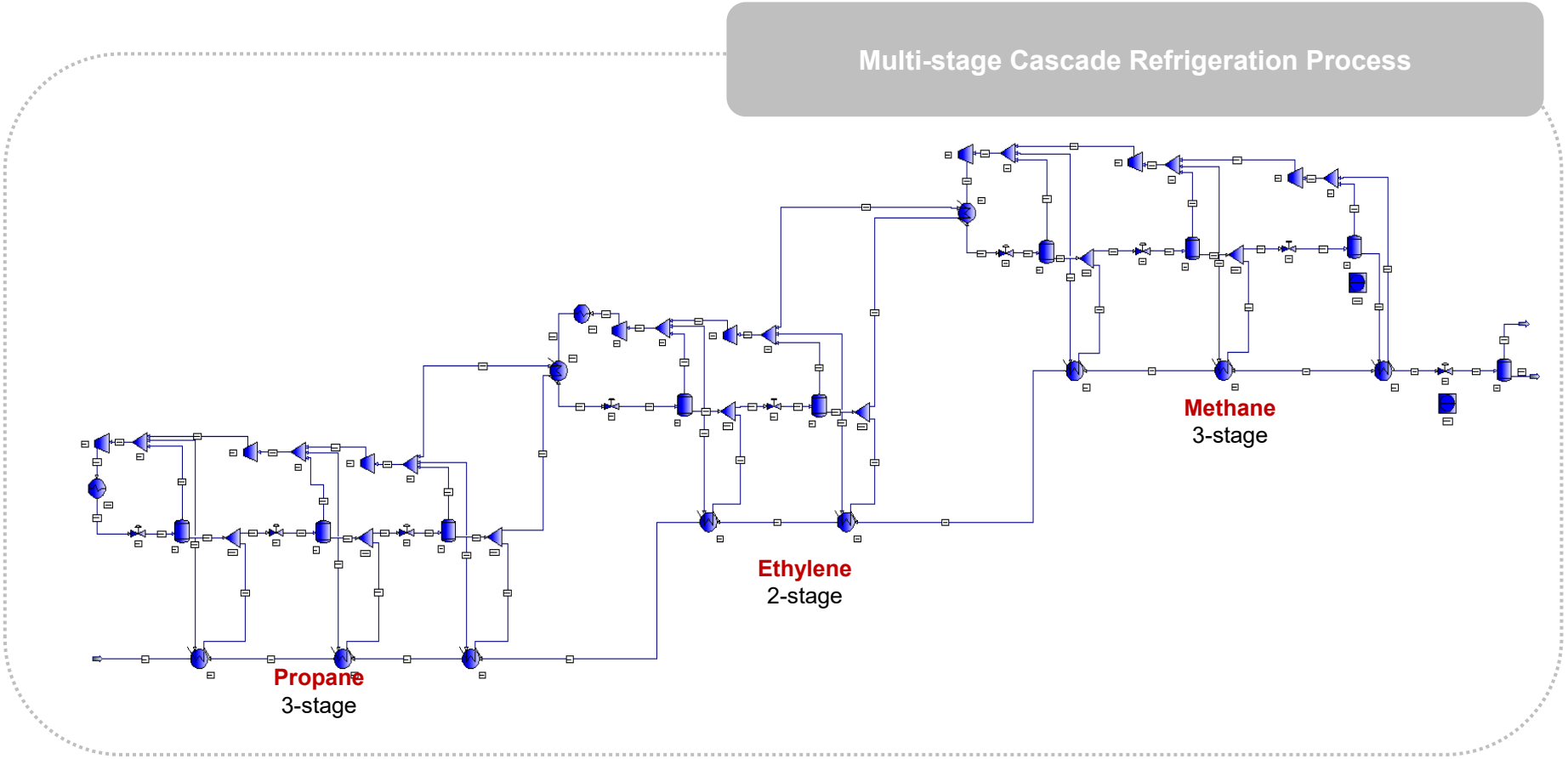
1단공정개요도.JNB
SigmaPlot 10.0 Notebook
63KB

SMR 완성.JNB
SigmaPlot 10.0 Notebook
62KB



SMR Process

다단 Cascade 냉동 사이클의 전산모사:



- 단순한 프로판 또는 프로필렌 냉동 사이클의 모사보다는 복잡한 냉동 사이클의 전산모사 능력 또한 매우 중요함

THANK YOU