
Multi-Stage Cascade Refrigeration System

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Cascade Refrigeration

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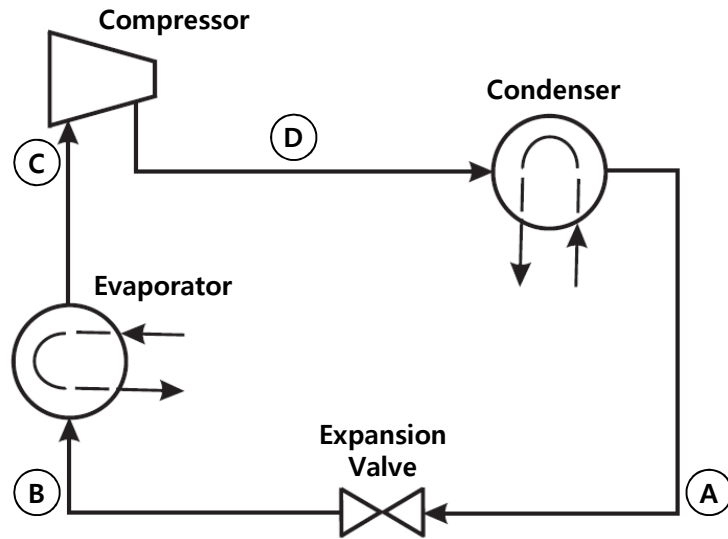
Multi-Stage Cascade Refrigeration Cycle & Results

Refrigeration Cycle and Input Condition of Natural Gas

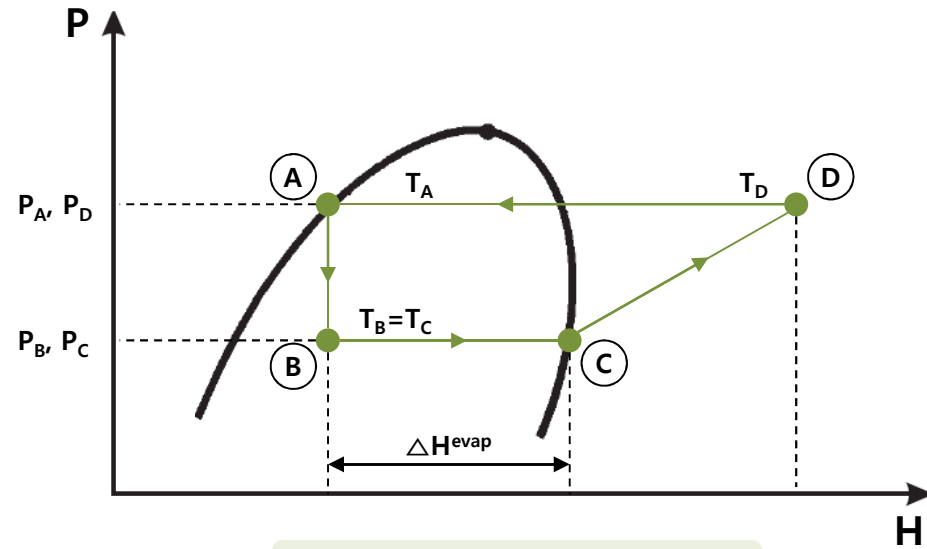
What is the refrigerator?

- By letting-down the pressure of chilled and highly compressed refrigerant, we can obtain a cold temperature of refrigerant. By adjusting the pressure letting-down level, we can obtain a wanted temperature level of refrigerant.
- By cooling after compressing a vapor stream, we can obtain a liquefied refrigerant.

Ideal refrigeration Cycle



Process Flow Diagram



Pressure Enthalpy Diagram

By utilizing the Pressure-Enthalpy (P-H) diagram, the refrigeration cycle can be broken down into four distinct steps :

- (A) Expansion
- (B) Evaporation
- (C) Compression
- (D) Condensation

Input Condition of Natural Gas

Contents	Value
Pressure (bar)	53
Temperature (°C)	45
Flow Rate (kg/hr)	625,000

Component	Mole%
Nitrogen	0.22
Methane	91.33
Ethane	5.36
Propane	2.14
I-Butane	0.46
N-Butane	0.47
I-Pentane	0.01
N-Pentane	0.01
Total	100

Cascade Refrigeration

Cascade Refrigeration

Step01
Microsoft Office Visio 드로잉
135KB

Step01
PRO/II Simulation
730KB

E01

Pressure drop(Hot Side) : 0.5bar
Minimum of [Hot Out-Cold In]
and [Hot In-Cold Out] : 3 °C
Refrigerant Component : C3
Refrigerant Temp. : 11.075 °C

E04

Pressure drop(Hot Side) : 0.5bar
Minimum of [Hot Out-Cold In]
and [Hot In-Cold Out] : 3 °C
Refrigerant Component : C2
Refrigerant Temp. : -69.74 °C

E06

Pressure drop(Hot Side) : 0.5bar
Minimum of [Hot Out-Cold In]
and [Hot In-Cold Out] : 3 °C
Refrigerant Component : C1
Refrigerant Temp. : -118.78 °C

E02

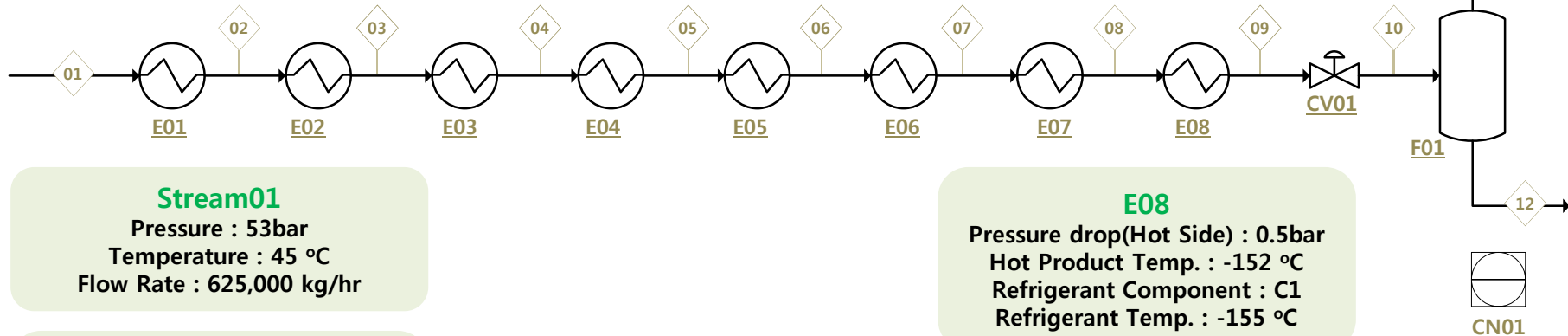
Pressure drop(Hot Side) : 0.5bar
Minimum of [Hot Out-Cold In]
and [Hot In-Cold Out] : 3 °C
Refrigerant Component : C3
Refrigerant Temp. : -17.148 °C

E05

Pressure drop(Hot Side) : 0.5bar
Hot Product Temp. : -92 °C
Refrigerant Component : C2
Refrigerant Temp. : -95 °C

E07

Pressure drop(Hot Side) : 0.5bar
Minimum of [Hot Out-Cold In]
and [Hot In-Cold Out] : 3 °C
Refrigerant Component : C1
Refrigerant Temp. : -139.29 °C



Stream01

Pressure : 53bar
Temperature : 45 °C
Flow Rate : 625,000 kg/hr

E08

Pressure drop(Hot Side) : 0.5bar
Hot Product Temp. : -152 °C
Refrigerant Component : C1
Refrigerant Temp. : -155 °C

E03

Pressure drop(Hot Side) : 0.5bar
Hot Product Temp. : -37 °C
Refrigerant Component : C3
Refrigerant Temp. : -40 °C

CV01

Pressure Drop : 0

F01

Adiabatic : duty 0

CN1 Condition & Result

PRO/II - Feedback Controller

UDM Range Help Overview Status Notes

Unit: Description:

Specification
Stream 12 Temperature in C = -162.00 within an absolute tolerance of 1.0000e-006

Variable
Flash F1 Pressure in bar Limits and Step Sizes...

Parameters
Maximum Number of Iterations: Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached:
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed:

Exit the window after saving all data

Data Review Window - Flash (Water on Bottom) - '...

Property	Value	Units
Flash Name	F1	
Flash Description		
Temperature	-162.0000	C
Pressure	0.9115	bar
DP	48.0885	bar
Duty	0.0000	M*x 10 ⁶ Kcal/hr

Flash Unit

Exit the window without saving any data

STREAM '01'

	TOTAL	VAPOR
RATE, KG-MOL/HR	35065.3581	35065.3581
TEMPERATURE, C	45.00	45.00
PRESSURE, BAR	53.00	53.00
MOLECULAR WEIGHT	17.8239	17.8239
FRACTION		1.0000

STREAM '12'

	TOTAL	LIQUID
RATE, KG-MOL/HR	32158.4636	32158.4636
TEMPERATURE, C	-162.00	-162.00
PRESSURE, BAR	9.1146E-01	9.1146E-01
MOLECULAR WEIGHT	17.9635	17.9635
FRACTION		1.0000

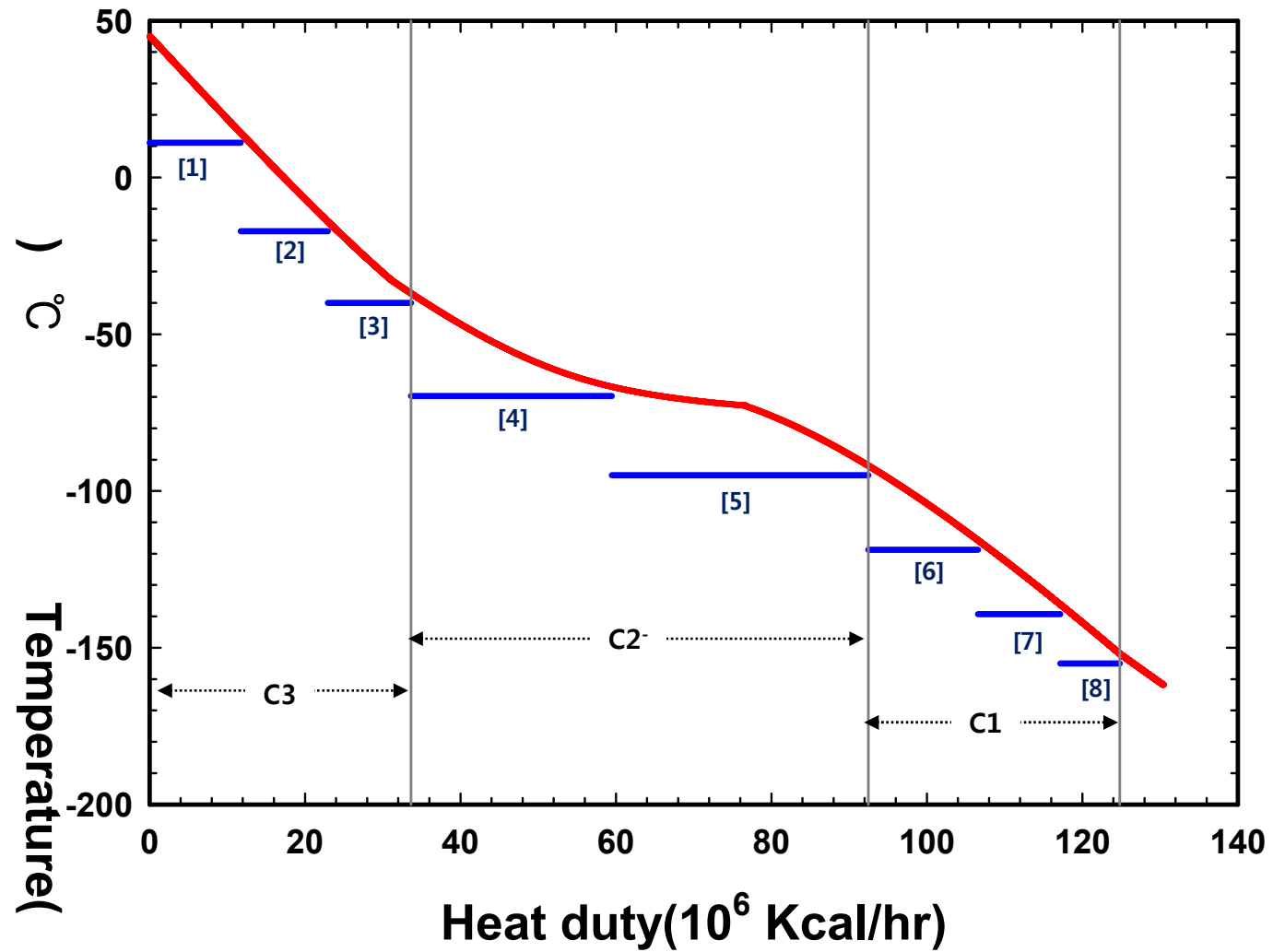
Rate of LNG Liquefaction

$$= \text{Stream12 Total Rate} / \text{Stream01 Total Rate} \times 100$$

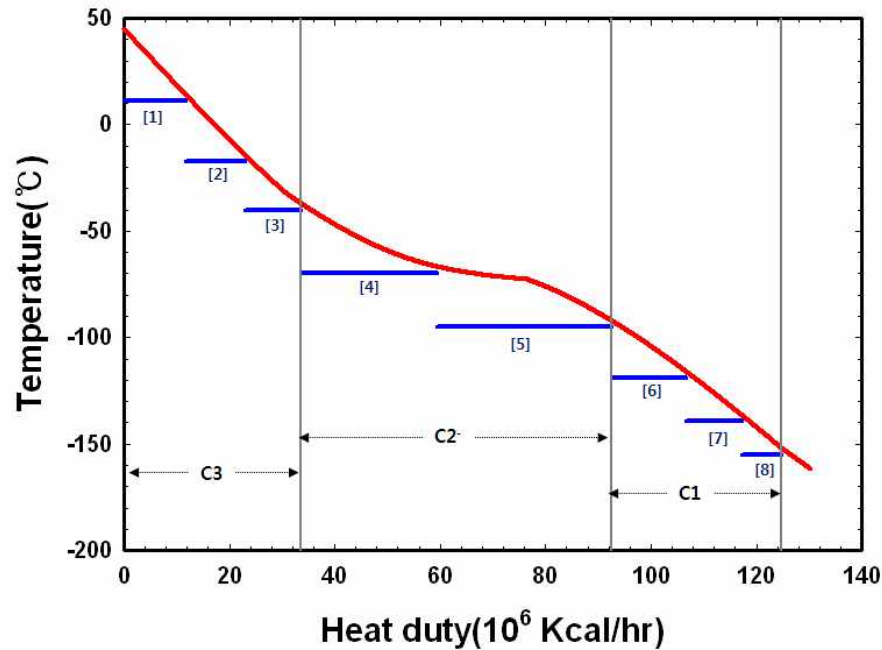
$$= 32158.4636 / 35065.3581 \times 100 = \mathbf{91.71\%}$$



Cascade Heating Curve



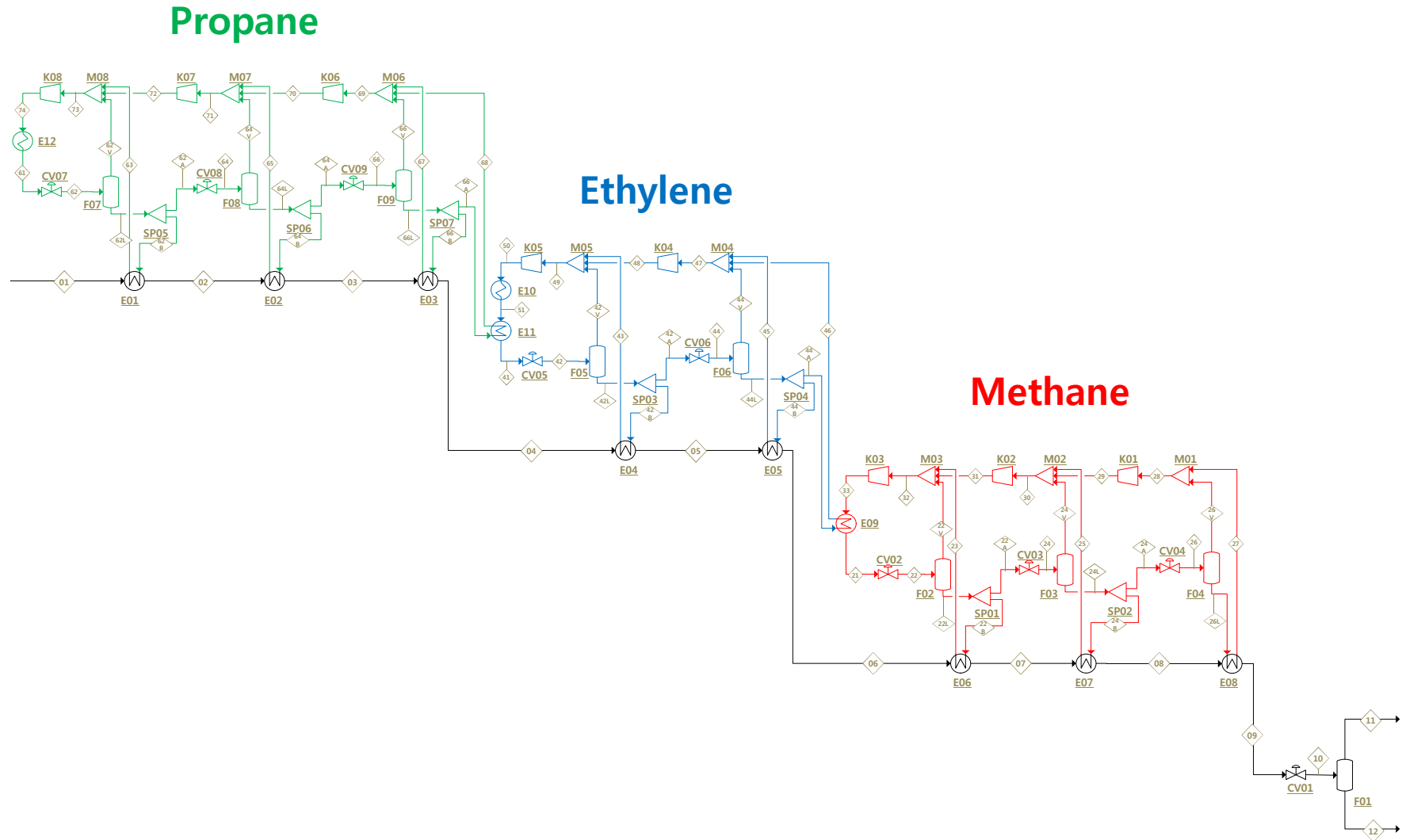
Cascade Heating Curve



	Temperature (°C)	Heat duty (*10 ⁶ Kcal/hr)	Flowrate of refrigerator (kg/hr)
[1]	11.08	11.7401	337452.036
[2]	-17.15	11.2082	117796.037
[3]	-40.00	10.6854	106008.027
[4]	-69.74	25.8445	253708.024
[5]	-95.00	33.0099	296820.610
[6]	-118.78	14.0877	149153.654
[7]	-139.29	10.5958	95617.043
[8]	-155.00	7.6387	64009.514
Total		124.8103	

Multi-Stage Cascade Refrigeration Cycle

Step09_Adding C3 Refrigeration Cycle
Microsoft Office Visio 드로잉
219KB



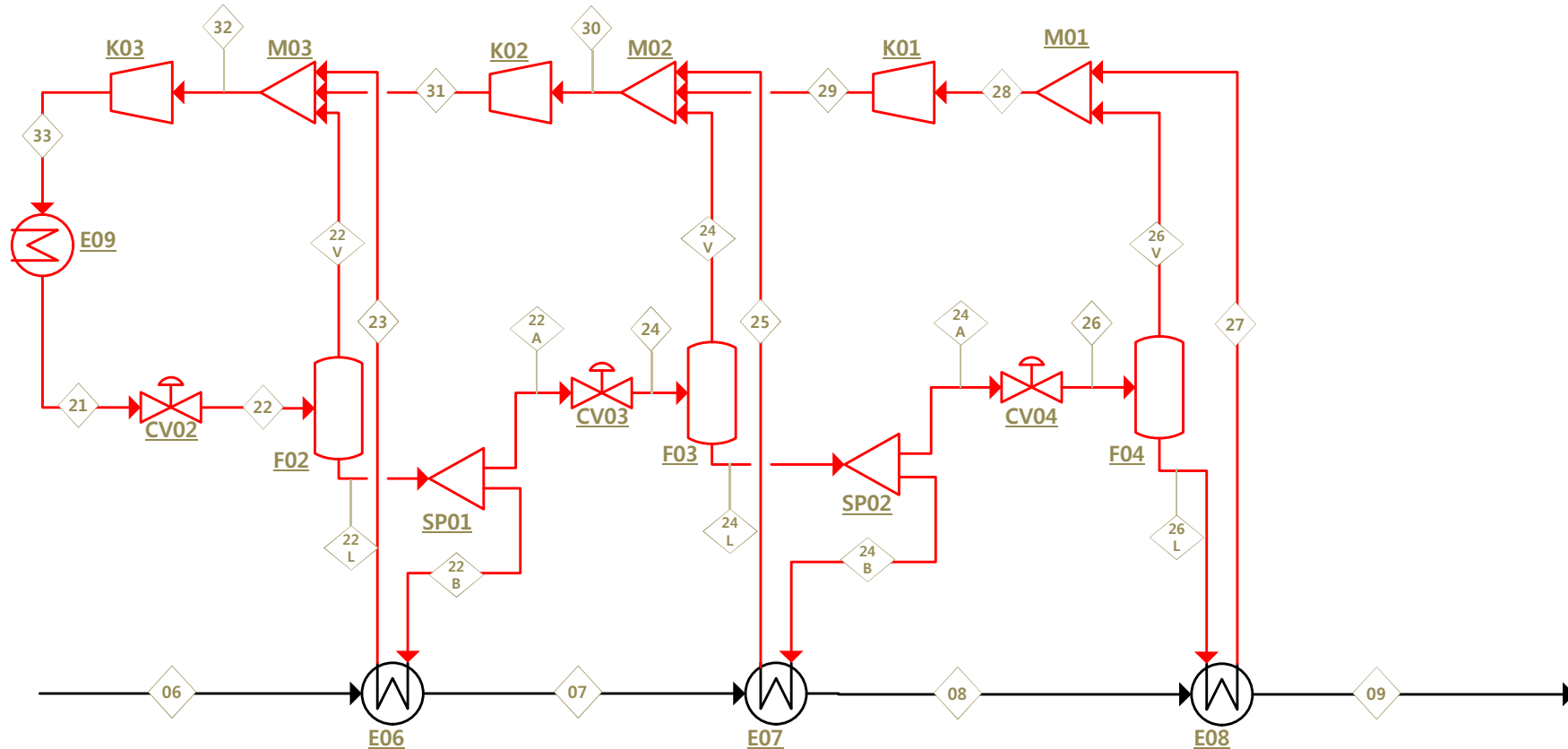
Three-Stage Refrigeration of methane

Three-Stage Refrigeration System

Second Stage Discharge Pressure(K02)
 = Second Suction Pressure * Ratio per stage
 = 4.6250 * 2.7448
 = **12.6947 bar**

First Stage Discharge Pressure(K01)
 = First Suction Pressure * Ratio per stage
 = 1.685 * 2.7448
 = **4.6250 bar**

$$\left(\frac{P_d}{P_s}\right)^{1/n} = \left(\frac{34.845}{1.685}\right)^{1/3} = 2.7448$$



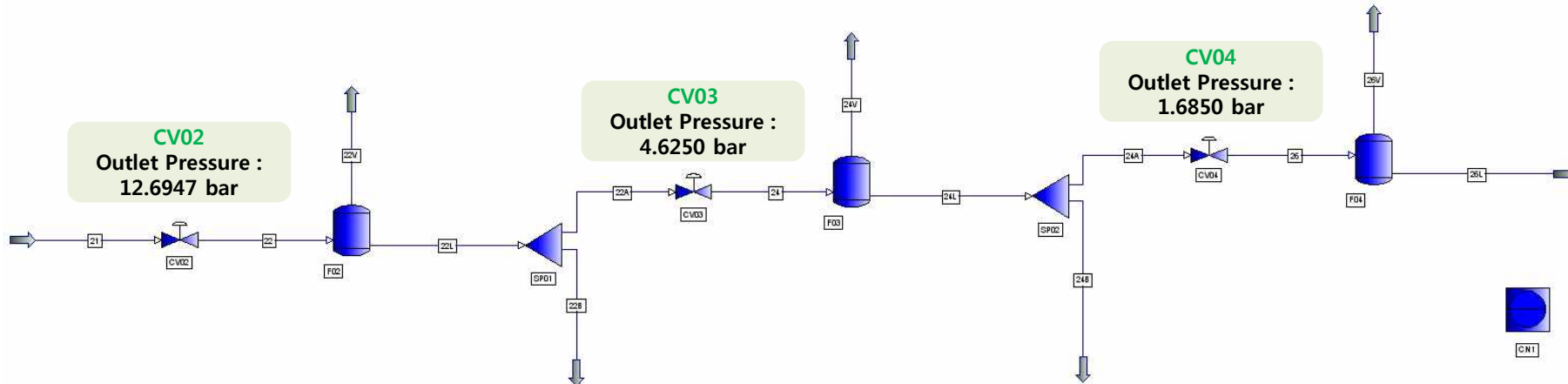
Temperature of Refrigerator(E06)
 = Dew point temperature of propane
 at 4.6250 bar
 = **-118.78 °C**

Temperature of Refrigerator(E07)
 = Dew point temperature of propane
 at 12.6947 bar
 = **-139.29 °C**



Calculation of total flowrate of methane

Step02_Calculation C1 Flowrate
PRO/II Simulation
628KB



PRO/II - Splitter

Unit: SP01 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 22B	Stream 22B Flowrate of All Components on a Wet basis in kg/hr = 1.4915e+005
2 22A	Parameter = value

Options When Feed is Inadequate to Satisfy Product Rate Specifications:

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Pressure Specification... Change Stream Specification Order... OK Cancel

Exit the window after saving all data

PRO/II - Splitter

Unit: SP02 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 24A	Parameter = value
2 24B	Stream 24B Flowrate of All Components on a Wet basis in kg/hr = 95611

Options When Feed is Inadequate to Satisfy Product Rate Specifications:

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Pressure Specification... Change Stream Specification Order... OK Cancel

Exit the window after saving all data

CN1 Condition & Result

PRO/II - Feedback Controller

UOM: Range: Help Overview Status Notes

Unit: Description:

Specification
Stream 26L Flowrate of All Components on a Wet basis in kg/hr = 64026, within a relative tolerance of 1.0000e-006

Variable
Stream 21 Flowrate in kg/hr Limits and Step Sizes...

Parameters
Maximum Number of Iterations: Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached:
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed:

Exit the window after saving all data

Total Flowrate of methane
35431.4336 Kgmol/hr = 568419.403 kg/hr

THERMODYNAMIC SYSTEM PR

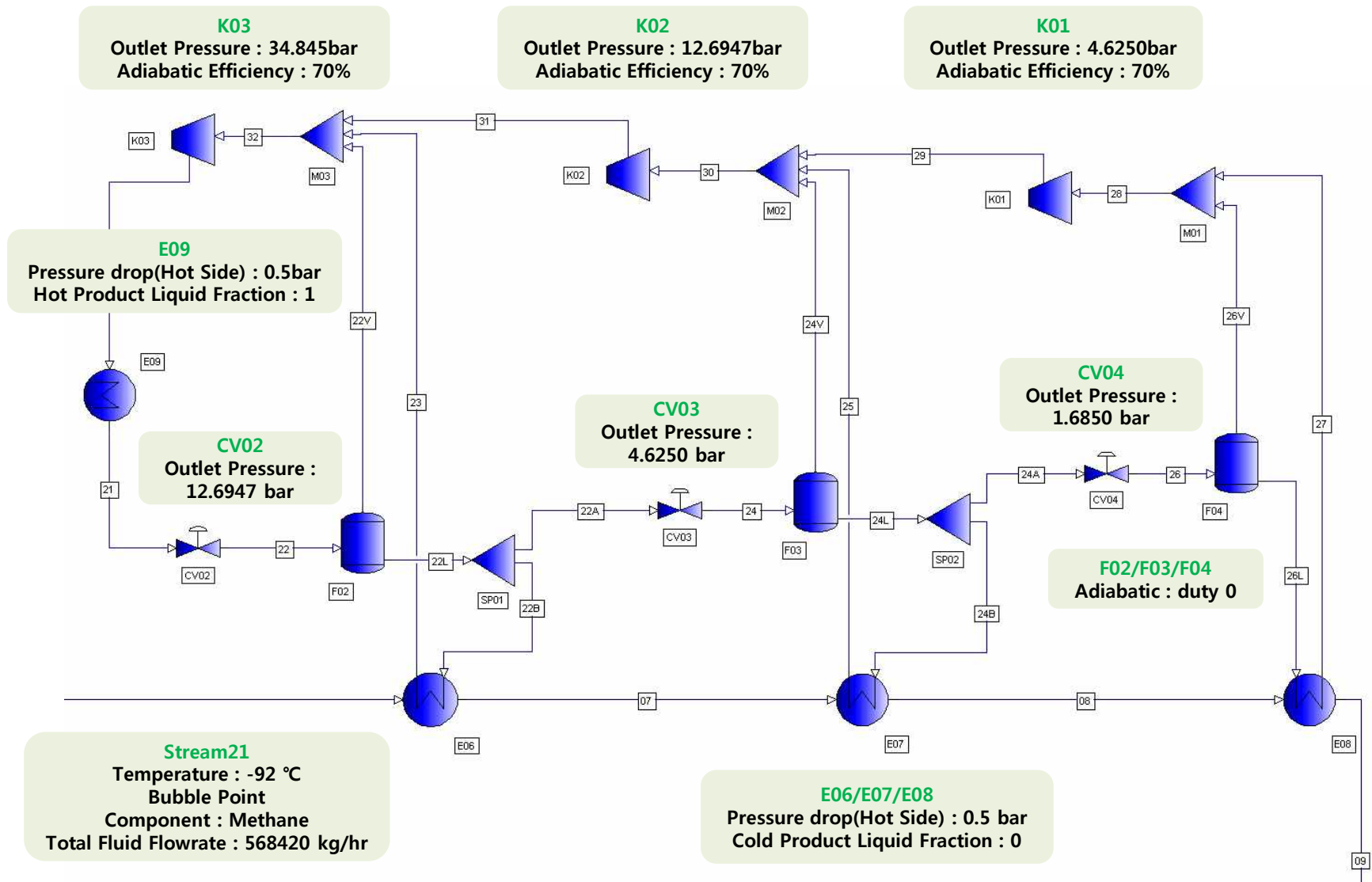
STREAM '21'

	TOTAL	LIQUID
RATE, KG-MOL/HR	35431.4336	35431.4336
TEMPERATURE, C	-92.00	-92.00
PRESSURE, BAR	34.35	34.35
MOLECULAR WEIGHT	16.0428	16.0428
FRACTION	1.0000	1.0000
ENTHALPY, KCAL/KG-MOL	-1362.4870	-1362.4870
CP, KCAL/KG-C	2.3932	2.3932
MOLAR FLOWRATES, KG-MOL/HR		
1 - N2	0.0000	0.0000
2 - C1	35431.4336	35431.4336
3 - C2	0.0000	0.0000
4 - C3	0.0000	0.0000
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	0.0000	0.0000
MOLAR COMPOSITIONS		
1 - N2	0.0000	0.0000
2 - C1	1.0000	1.0000
3 - C2	0.0000	0.0000
4 - C3	0.0000	0.0000
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	0.0000	0.0000

Three-Stage Refrigeration Cycle



Step03_Adding C1 Refrigeration Cycle
PRO/II Simulation
709KB

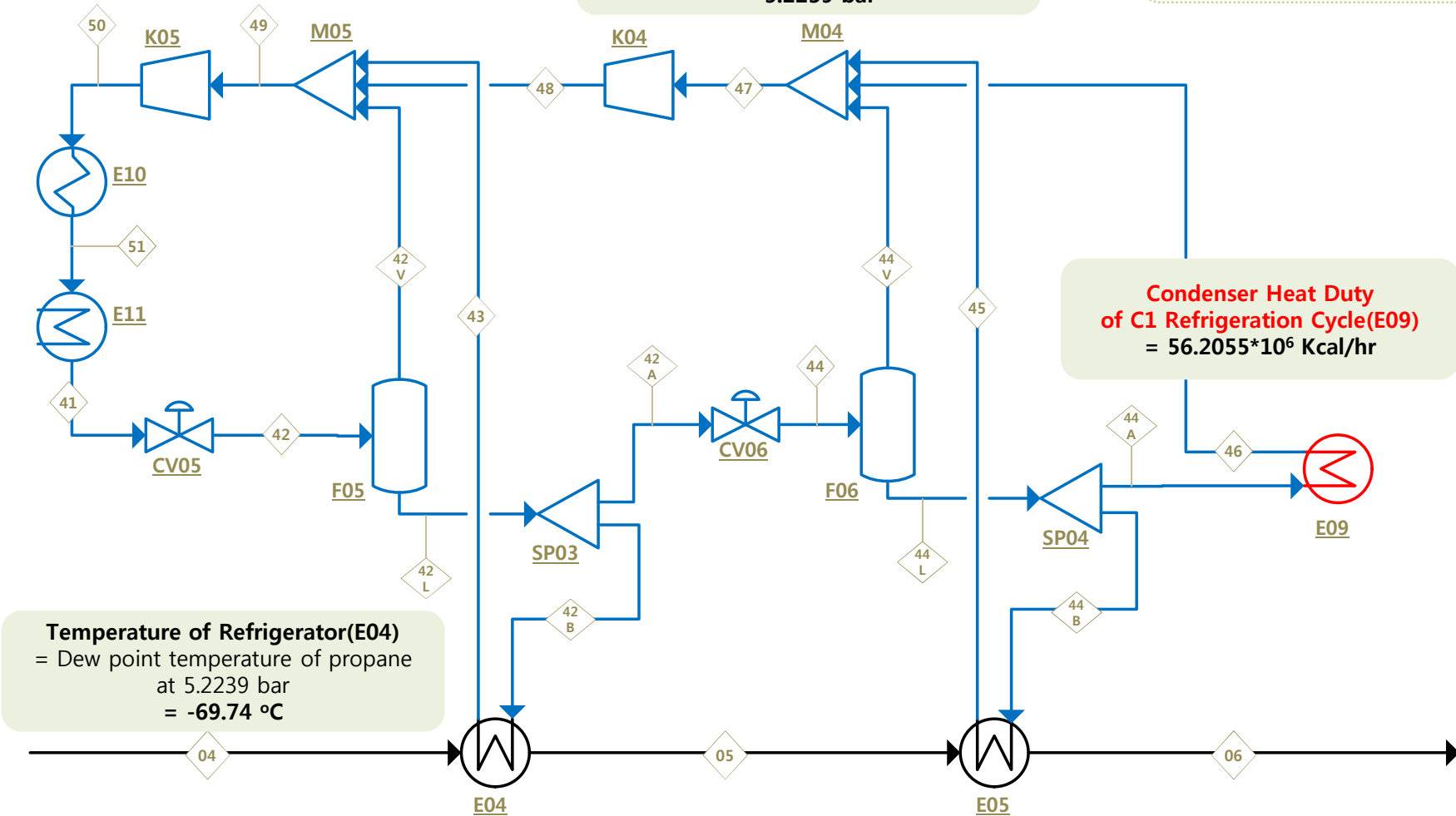


Two-Stage Refrigeration of ethylene

Two-Stage Refrigeration System

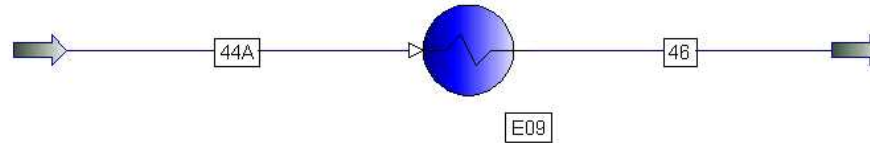
First Stage Discharge Pressure(K04)
 = Suction Pressure * Ratio per stage
 = 1.665 * 3.1375
 = 5.2239 bar

$$\left(\frac{P_d}{P_s}\right)^{1/n} = \left(\frac{16.390}{1.665}\right)^{1/2} = 3.1375$$



Calculation of total flowrate of ethylene

Step04_Calculation C2 Flowrate
PRO/II Simulation
627KB



CN2

Stream Name	44A	46
Temperature (°C)	-95.00	-95.00
Pressure (bar)	1.665	1.665
Flowrate (kgmole/hr)	18015.211	18015.211
Flowrate (kg/hr)	505395.121	505395.121
E09 Duty	56.2055*10⁶ Kcal/hr	

PRO/II - Feedback Controller

UDM Range Help Overview Status Notes

Unit: Description:

Specification
Stream 46 Temperature in C = -95.000 within a relative tolerance of 1.0000e-006

Variable
[Stream 44A Flowrate in kg-mol/hr](#) Limits and Step Sizes...

Parameters
Maximum Number of Iterations: Print Results for Each Iteration

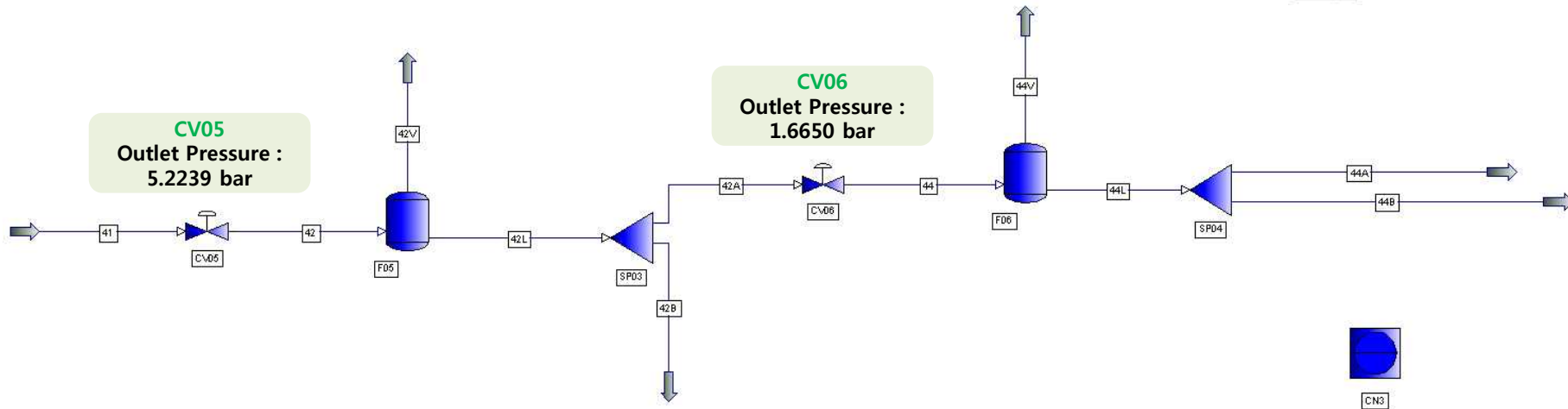
Action if Minimum/Maximum Limits are reached
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed:

Exit the window after saving all data

Calculation of total flowrate of ethylene

Step05_Calculation C2 Flowrate
PRO/II Simulation
629KB



PRO/II - Splitter

Unit: SP03 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 42B	Stream 42B Flowrate of All Components on a Wet basis in kg/hr = 2.5376e+005
2 42A	Parameter = value

Options When Feed is Inadequate to Satisfy Product Rate Specifications:

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Exit the window after saving all data

PRO/II - Splitter

Unit: SP04 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 44B	Parameter = value
2 44A	Stream 44A Flowrate of All Components on a Wet basis in kg/hr = 5.0540e+005

Options When Feed is Inadequate to Satisfy Product Rate Specifications:

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Exit the window after saving all data



CN3 Condition & Result

PRO/II - Feedback Controller

UQM Range Help Overview Status Notes

Unit: CN3 Description:

Specification
Stream 44B Flowrate of All Components on a Wet basis in kg/hr = 2.9677e+005 within a relative tolerance of 1.0000e-006

Variable
Stream 41 Flowrate in kg/hr Limits and Step Sizes...

Parameters
Maximum Number of Iterations: 10 Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached:
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed: Calculated

OK Cancel

Exit the window after saving all data

Total Flowrate of ethylene
53164.75 Kgmol/hr = 1491473.264 kg/hr

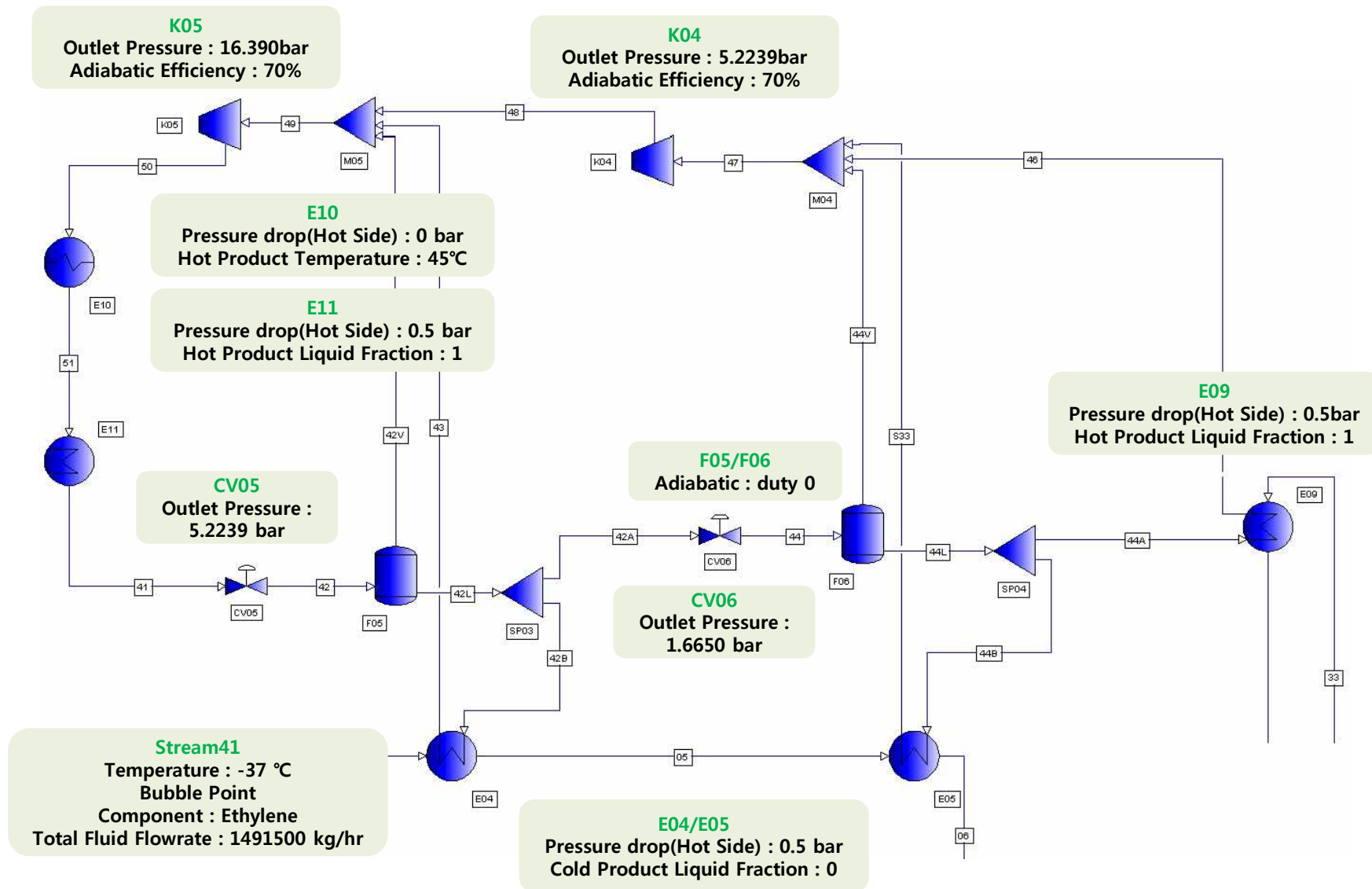
THERMODYNAMIC SYSTEM PR

STREAM '41'

	TOTAL	LIQUID
RATE, KG-MOL/HR	53164.7500	53164.7500
TEMPERATURE, C	-37.00	-37.00
PRESSURE, BAR	15.89	15.89
MOLECULAR WEIGHT	28.0538	28.0538
FRACTION		1.0000
ENTHALPY, KCAL/KG-MOL	-873.8201	-873.8201
CP, KCAL/KG-C	0.7549	0.7549
MOLAR FLOWRATES, KG-MOL/HR		
1 - N2	0.0000	0.0000
2 - C1	0.0000	0.0000
3 - C2	0.0000	0.0000
4 - C3	0.0000	0.0000
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	53164.7500	53164.7500
MOLAR COMPOSITIONS		
1 - N2	0.0000	0.0000
2 - C1	0.0000	0.0000
3 - C2	0.0000	0.0000
4 - C3	0.0000	0.0000
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	1.0000	1.0000



Two-Stage Refrigeration Cycle



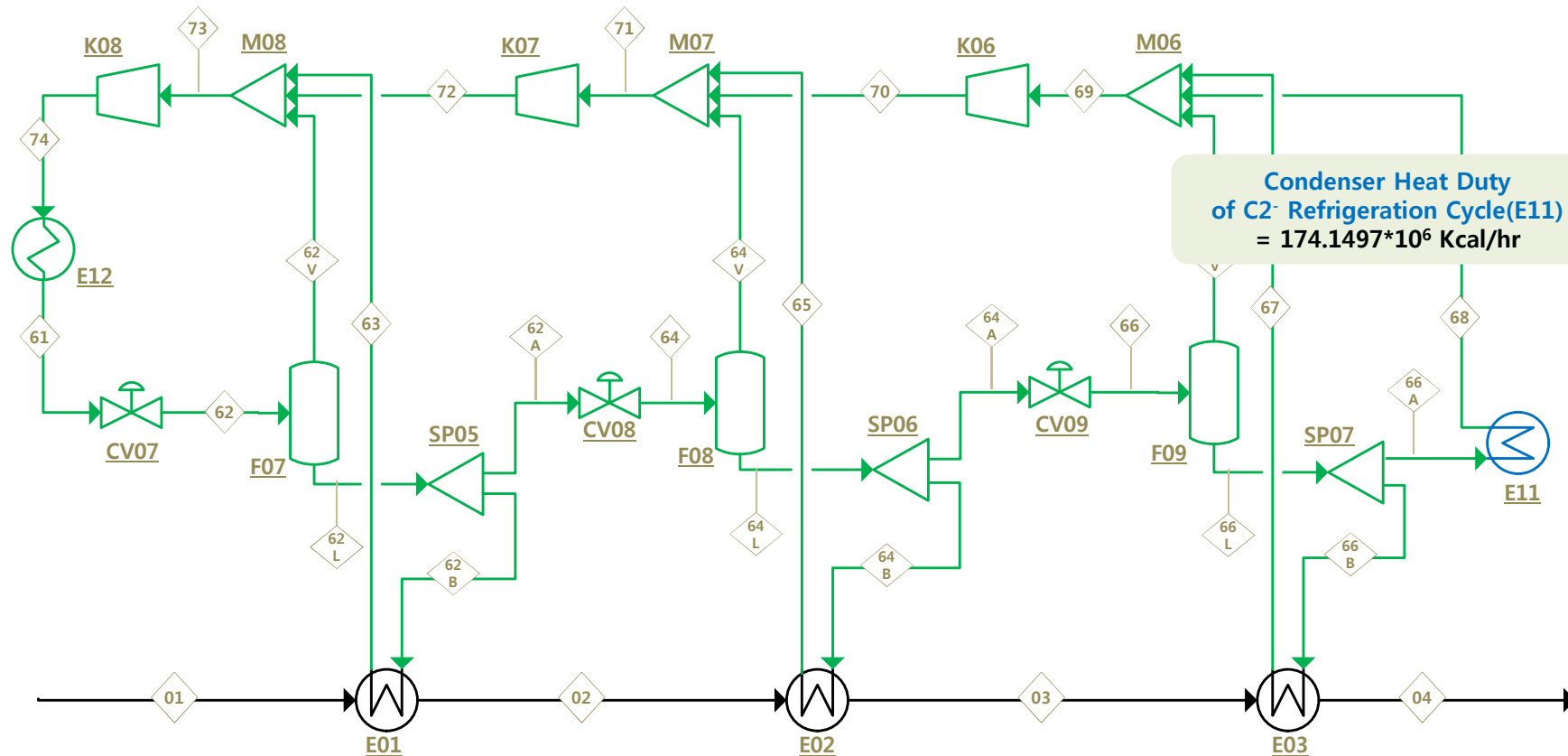
Three-Stage Refrigeration of propane

Three-Stage Refrigeration System

Second Stage Discharge Pressure(K07)
 = Second Suction Pressure * Ratio per stage
 = 2.7013 * 2.4249
 = 6.5505 bar

First Stage Discharge Pressure(K06)
 = First Suction Pressure * Ratio per stage
 = 1.114 * 2.4249
 = 2.7013 bar

$$\left(\frac{P_d}{P_s}\right)^{1/n} = \left(\frac{15.885}{1.114}\right)^{1/3} = 2.4249$$



Condenser Heat Duty of C2 Refrigeration Cycle(E11)
 = 174.1497*10⁶ Kcal/hr

Temperature of Refrigerator(E01)
 = Dew point temperature of propane
 at 2.7013 bar
 = -17.148 °C

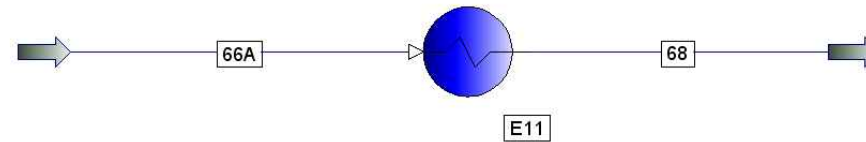
Temperature of Refrigerator(E02)
 = Dew point temperature of propane
 at 6.5505 bar
 = 11.075 °C



Calculation of total flowrate of propane



Step07_Calculation C1 Flowrate
PRO/II Simulation
627KB



CN4

Stream Name	66A	68
Temperature (°C)	-40.00	-39.99
Pressure (bar)	1.114	1.114
Flowrate (kgmole/hr)	39180.305	39180.305
Flowrate (kg/hr)	1727714.258	1727714.258
E09 Duty	174.1497*10⁶ Kcal/hr	

PRO/II - Feedback Controller

UOM Range Help Overview Status Notes

Unit: Description:

Specification
Stream 68 Temperature in C = -40.000 within a relative tolerance of 1.0000e-006

Variable
[Stream 66A Flowrate in kg-mol/hr](#) Limits and Step Sizes...

Parameters
Maximum Number of Iterations: Print Results for Each Iteration

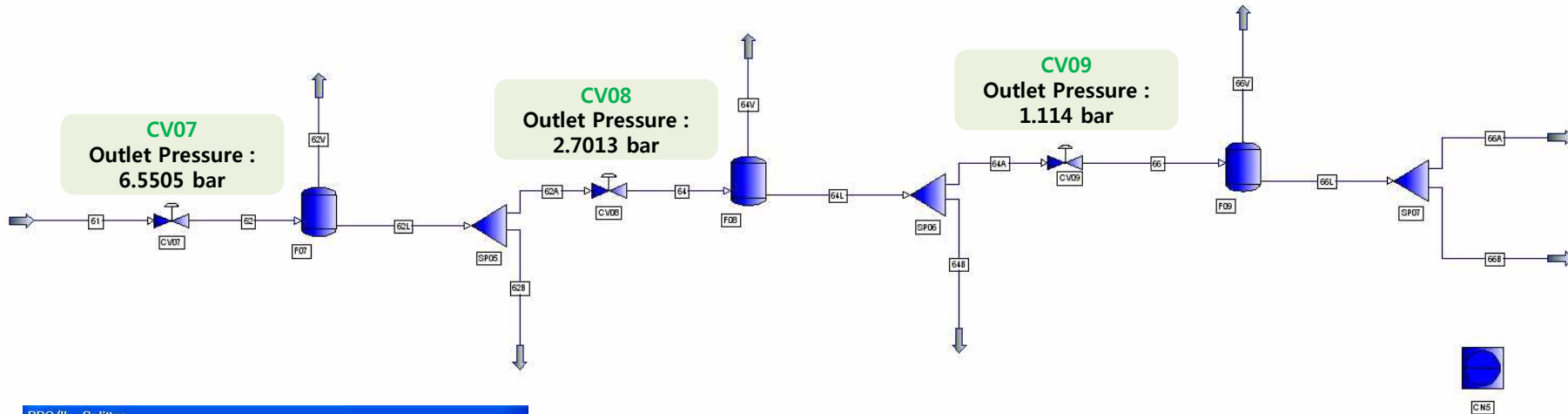
Action if Minimum/Maximum Limits are reached
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed:

Exit the window after saving all data

Calculation of total flowrate of propane

Step08_Calculation C2 Flowrate
PRO/II Simulation
630KB



PRO/II - Splitter

Unit: SP05 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 62B	Stream 62B Flowrate of All Components on a Wet basis in kg/hr = 1.3609e+005
2 62A	Parameter = value

Options When Feed is Inadequate to Satisfy Product Rate Specifications

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Pressure Specification... Change Stream Specification Order... OK Cancel

Exit the window after saving all data

PRO/II - Splitter

Unit: SP06 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 64A	Parameter = value
2 64B	Stream 64B Flowrate of All Components on a Wet basis in kg/hr = 1.1782e+005

Options When Feed is Inadequate to Satisfy Product Rate Specifications

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Pressure Specification... Change Stream Specification Order... OK Cancel

Exit the window after saving all data

PRO/II - Splitter

Unit: SP07 Description: Thermodynamic System: Default (PR01)

Stream	Specification
1 66B	Parameter = value
2 66A	Stream 66A Flowrate of All Components on a Wet basis in kg/hr = 1.7277e+006

Options When Feed is Inadequate to Satisfy Product Rate Specifications

Satisfy Each Specification in Order Until Feed is Exhausted

Satisfy Each Specification and Normalize Flowrates if Needed

Pressure Specification... Change Stream Specification Order... OK Cancel

Exit the window after saving all data

CN5 Condition & Result

PRO/II - Feedback Controller

UQM Range Help Overview Status Notes

Unit: CN5 Description:

Specification
Stream 66B Flowrate of All Components on a Wet basis in kg/hr = 1.0601e+005 within a relative tolerance of 1.0000e-006

Variable
Stream 61 Flowrate in kg/hr Limits and Step Sizes...

Parameters
Maximum Number of Iterations: 10 Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached:
 Accept as Solved if Limits are Reached
 Fail Unit and Stop Calculations if Limits are Reached
 Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed: Calculated

OK Cancel

Exit the window after saving all data

Total Flowrate of propane
87113.3668 Kgmol/hr = 3841394.579 kg/hr

THERMODYNAMIC SYSTEM PR

STREAM '61'

	TOTAL	LIQUID
RATE, KG-MOL/HR	87113.3668	87113.3668
TEMPERATURE, C	45.00	45.00
PRESSURE, BAR	15.38	15.38
MOLECULAR WEIGHT	44.0965	44.0965
FRACTION		1.0000
ENTHALPY, KCAL/KG-MOL	1363.2541	1363.2541
CP, KCAL/KG-C	0.7693	0.7693

MOLAR FLOWRATES, KG-MOL/HR

1 - N2	0.0000	0.0000
2 - C1	0.0000	0.0000
3 - C2	0.0000	0.0000
4 - C3	87113.3668	87113.3668
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	0.0000	0.0000

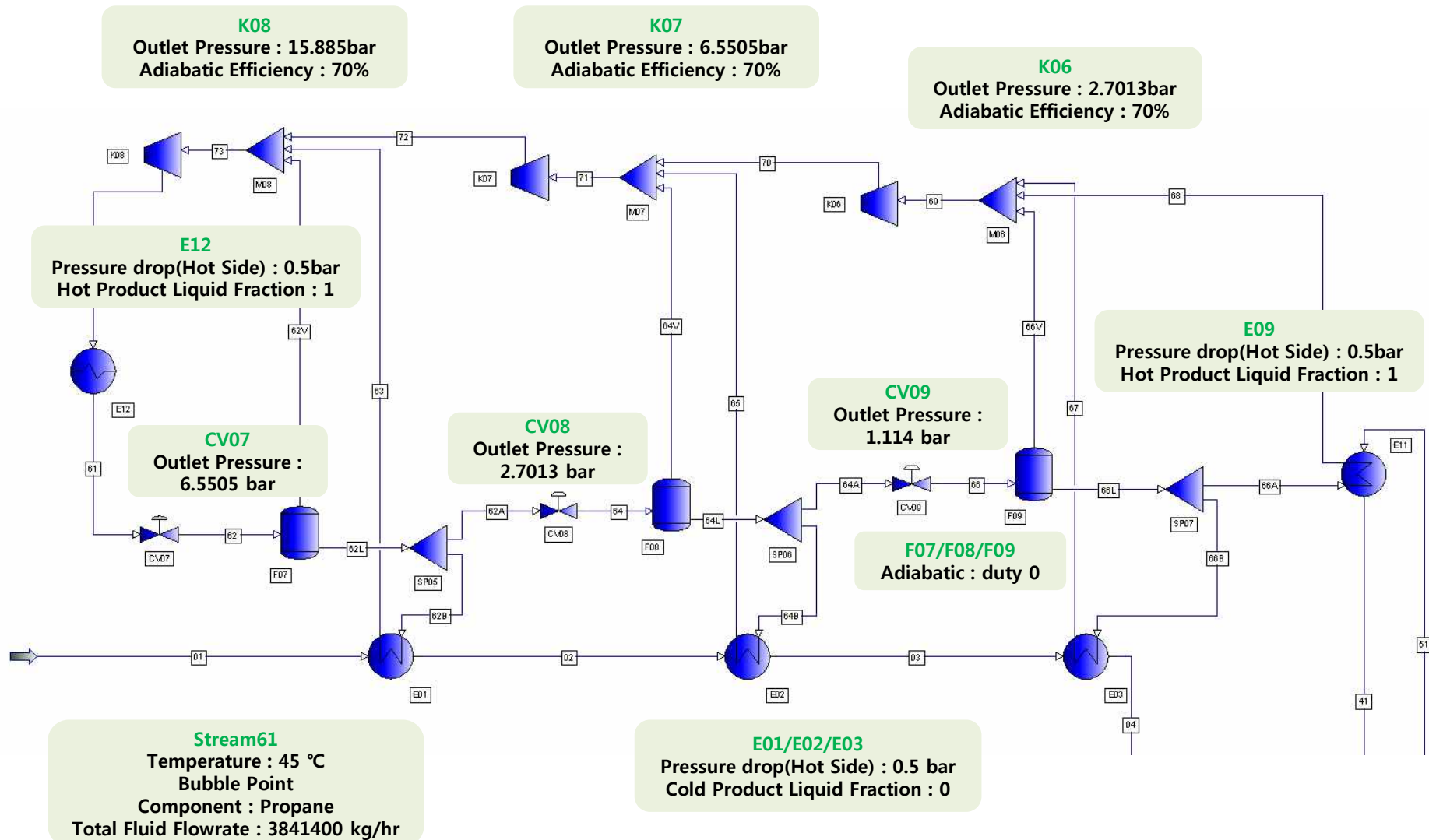
MOLAR COMPOSITIONS

1 - N2	0.0000	0.0000
2 - C1	0.0000	0.0000
3 - C2	0.0000	0.0000
4 - C3	1.0000	1.0000
5 - IC4	0.0000	0.0000
6 - NC4	0.0000	0.0000
7 - IC5	0.0000	0.0000
8 - NC5	0.0000	0.0000
9 - C2-	0.0000	0.0000

Three-Stage Refrigeration Cycle



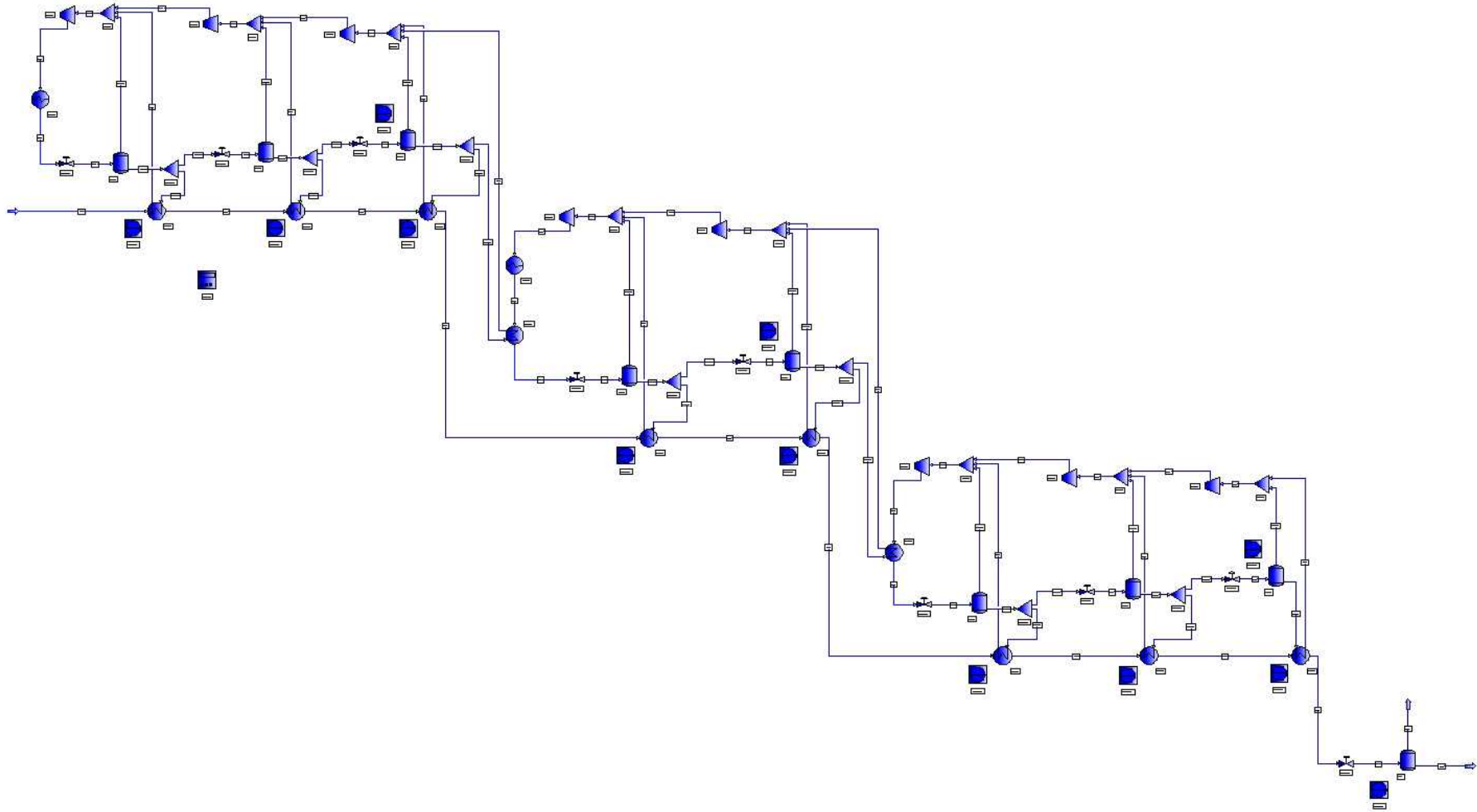
Step09_Adding C3 Refrigeration Cycle
PRO/II Simulation
719KB



Multi-Stage Cascade Refrigeration Cycle & Results

Multi-Stage Cascade Refrigeration Cycle

Step10_Multi-stage Cascade
PRO/II Simulation
738KB



Results of Calculator

Refrigerator	Contents	Actual Work (kW)
Propane	K08	6.97935E+04
	K07	4.65535E+04
	K06	3.26463E+04
Ethylene	K05	4.93771E+04
	K04	2.40789E+04
Methane	K03	1.94100E+04
	K02	6.41777E+03
	K01	1.91124E+03
Total		2.50188E+05
LNG Flowrate (kg/hr)		577679.6567

Specific Power for produced LNG [kWh/kg]
= 0.433 kWh/kg LNG

**Thank you
for your attention**

