LNG Cold Heat Price for Various Single Refrigerants and Cascade Refrigerants

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1 Abstract

Abstract:

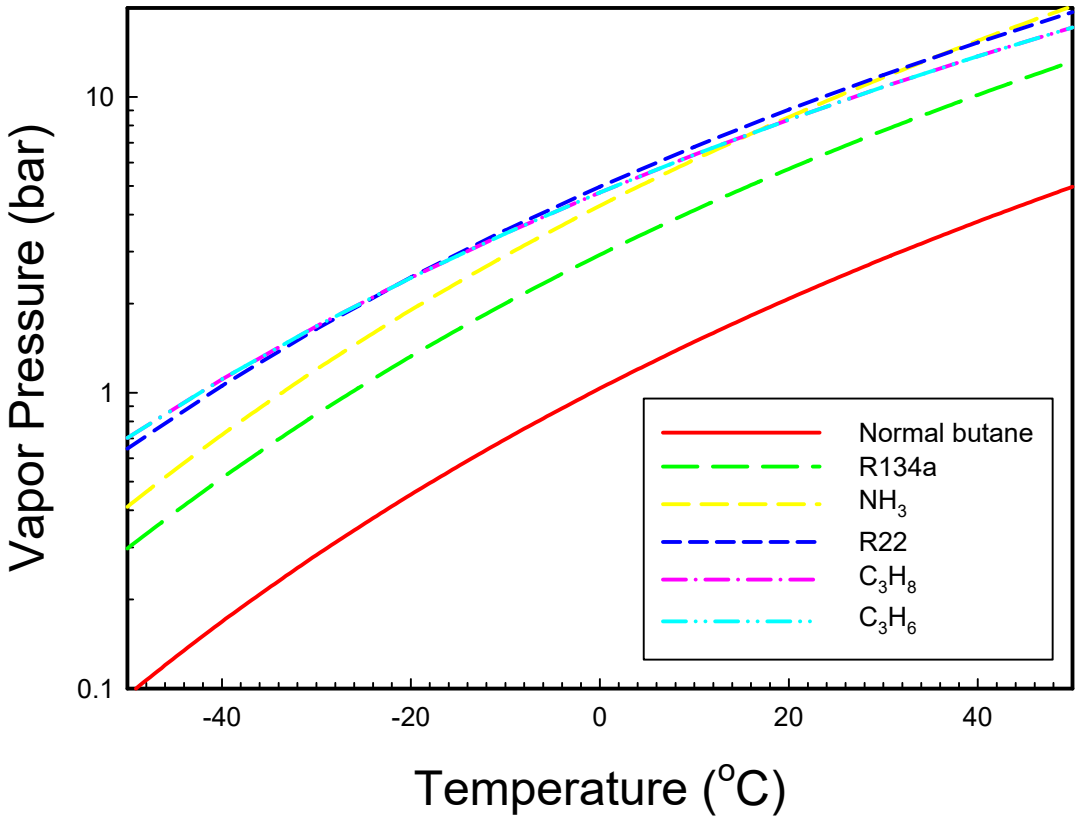
In this work, the price contained in the liquefied natural gas cold heat have been estimated to cool and liquefy the various refrigerants by exchanging heat with LNG since the LNG supply temperature is too low to liquefy almost all kinds of refrigerants.
Pure component refrigeration cycle for 35 refrigerants and two kinds of cascade refrigeration cycle were tested for the estimation of cold heat price contained in the LNG.
Peng-Robinson equation of state model with Twu's alpha function was utilized built-in PRO/II with PROVISION V10.2 for the modeling of refrigeration cycle and cold heat price estimation.
Through this study, it was concluded that the prices in the LNG was inversely proportional to refrigerant supply temperature since compressor power is increasing when the refrigerant temperature is lower.

2 Physical Properties of Pure Component Refrigerants

Physical Properties of Pure Component Refrigerants:

		IUPAC Chemical Name	Molecular Formula	Normal Boiling Point (°C)	Critical Temperature (°C)
1	R152	1,2-Difluoroethane	C2H4F2	10.50	171.85
2	R21	Dichlorofluoromethane	CHFCl2	8.90	178.43
3	R133A	1-Chloro-2,2,2-Trifluoroethane	C2H2F3Cl	6.10	156.85
4	R114	1,2-Dichlorotetrafluoroethane	C2F4Cl2	3.77	145.70
5	R600	Butane	C4H10	-0.50	151.97
6	R3-1-10	Decafluorobutane	C4F10	-2.01	113.20
7	R12B1	Bromochlorodifluoromethane	CBrClF2	-4.01	153.00
8	R318	Octafluorocyclobutane	C4F8	-5.98	115.22
9	R630	Methylamine	CH3NH2	-6.33	156.90
10	R31	Chlorofluoromethane	CH2FCl	-9.09	153.85
11	R764	Sulfur dioxide	SO2	-10.02	157.60
12	R600A	Isobutane	C4H10	-11.72	134.99
13	R124	1-Chloro-1,2,2,2-tetrafluoroethane	C2HF4Cl	-12.10	122.50
14	R245	Pentafluoropropane	C3H3F5	-17.65	106.96
15	R134	1,1,2,2-Tetrafluoroethane	C2H2F4	-23.00	118.65
16	R40	Chloromethane	CH3Cl	-24.22	143.10
17	RE170	Dimethyl ether	CH3OCH3	-24.84	126.95
18	R152A	1,1-Difluoroethane	C2H4F2	-25.80	113.29
19	R134A	1,1,1,2-Tetrafluoroethane	C2H2F4	-26.00	101.15
20	R1113	Chlorotrifluoroethylene	C2ClF3	-27.85	106.00
21	R1234YF	2,3,3,3-Tetrafluoropropene	C3H2F4	-29.42	94.80
22	R1216	Hexafluoropropylene	C3F6	-29.60	94.85
23	RFE36	Hexafluoropropane	C3H2F6	-29.60	94.85
24	R12	Dichlorodifluoromethane	CCl2F2	-29.79	111.80
25	R717	Ammonia	NH3	-33.43	132.50
26	R218	Octafluoropropane	C3F8	-36.75	71.90
27	R161	Fluoroethane	C2H5F	-37.70	102.16
28	R115	Chloropentafluoroethane	C2F5Cl	-39.11	80.00
29	R22	Chlorodifluoromethane	CHClF2	-40.83	96.15
30	R290	Propane	C3H8	-42.04	96.68
31	R143 (*)	1,1,2-Trifluoroethane	C2H3F3	-47.40	73.10
32	R1270	Propene (Propylene)	C3H6	-47.69	92.42
33	R125	Pentafluoroethane	C2HF5	-48.00	66.04
34	R32	Difluoromethane	CH2F2	-51.65	78.45
35	R13B1	Bromotrifluoromethane	CBrF3	-57.89	67.00

Vapor Pressures for Refrigerants:



Temperature range: from melting to its critical

3 LNG Compositions

KOGAS 수입 LNG의 조성:

	Case 1	Case 2	Case 3	Case 4
	Lean	Rich	Max N_2	Typical
Nitrogen	0.00	0.00	1.00	0.04
Methane	96.74	85.12	94.33	89.26
Ethane	1.89	8.63	1.97	8.64
Propane	0.68	4.14	2.50	1.44
i-Butane	0.34	1.10	0.10	0.27
N-Butane	0.34	0.90	0.10	0.35
i-Pentane	0.01	0.10	0.00	0.00
N-Pentane	0.00	0.01	0.00	0.00
MW	16.791	19.320	17.189	17.924
GHV	9,882	11,163	9,975	10,450
Sp. Gr.	0.434	0.478	0.448	0.455

KOGAS 수입 LNG의 조성 (1): 개질기 검토 시에 적용

Stream No.	1	2	3	4	5	6	7
Case	Lean	Rich	Max N_2	Typical 1	Typical 2	최저	순수메탄
Nitrogen	0.00	0.00	1.00	0.20	0.2	0.19	0
Methane	96.74	85.12	94.33	91.31	93.08	96.65	100
Ethane	1.89	8.63	1.97	5.47	4.49	0.58	0
Propane	0.68	4.14	2.50	2.06	1.53	0.08	0
i-Butane	0.34	1.10	0.10	0.45	0.33	0.11	0
N-Butane	0.34	0.90	0.10	0.48	0.36	0	0
i-Pentane	0.01	0.10	0.00	0.02	0.02	0	0
N-Pentane	0.00	0.01	0.00	0.00	0.00	0	0
MW	16.7904	19.3180	17.2243	17.8146	17.4272	16.2198	16.0428
GHV	9,875	11,154	9,940	10,363	10,167	9,557	9,497
LHV	8,904	10,097	8,967	9,360	9,177	8,607	8,551

보령LNG터미널에서 취급하는 LNG의 조성:

Component	Composition (Mol%)		
	Case 1 (Lean)	Case 2 (Typical)	Case 3 (Rich)
Nitrogen	0.2	0.19	0.00
Methane	97.70	96.74	85.12
Ethane	2.10	2.35	8.63
Propane	-	0.50	4.14
i-Butane	-	0.09	1.10
n-Butane	-	0.11	0.90
i-Pentane	-	0.02	0.10
n-Pentane	-	-	0.01
Molecular weight	16.36	16.63	19.32
Gross heating value, @ 0 ℃ & 1 atm(kcal/Nm^3)	9,631	9,768	11,195
SG of liquid	0.425	0.430	0.478
Gas compressibility factor @ 0 ℃ & 1 atm	0.9969	0.9968	0.9957
Gas density (real) @ 0 ℃ & 1atm (kg/Nm^3)	0.7322	0.7444	0.8656

KOGAS와 동일

* Nm^3은 0℃, 1 atm 에서 측정

보령LNG터미널 도입 선적지 별 LNG의 조성:

보령LNG터미널 도입 선적지 별 성분

date :2016.12 ~ 2018.07

항차(도입)		24	9	7	7
1	Methane	**94.14**	**95.88**	**91.12**	**96.78**
2	Ethane	**4.13**	**3.75**	**5.94**	**2.36**
3	Propane	**1.03**	**0.27**	**2.32**	**0.48**
4	i-Butane	**0.21**	**0.04**	**0.33**	**0.09**
5	n-Butane	**0.25**	**0.03**	**0.26**	**0.11**
6	i-Pentane	**0.05**	**0.00**	**0.00**	**0.02**
7	n-Pentane	**0.01**	**0.00**	**0.00**	**0.00**
8	Hexanes Plus	**0.00**	**0.00**	**0.00**	**0.00**
9	Nitrogen	**0.18**	**0.03**	**0.03**	**0.16**
10	Carbon Dioxide	**0.00**	**0.00**	**0.00**	**0.00**
11	Oxygen	**0.00**	**0.00**	**0.00**	**0.00**

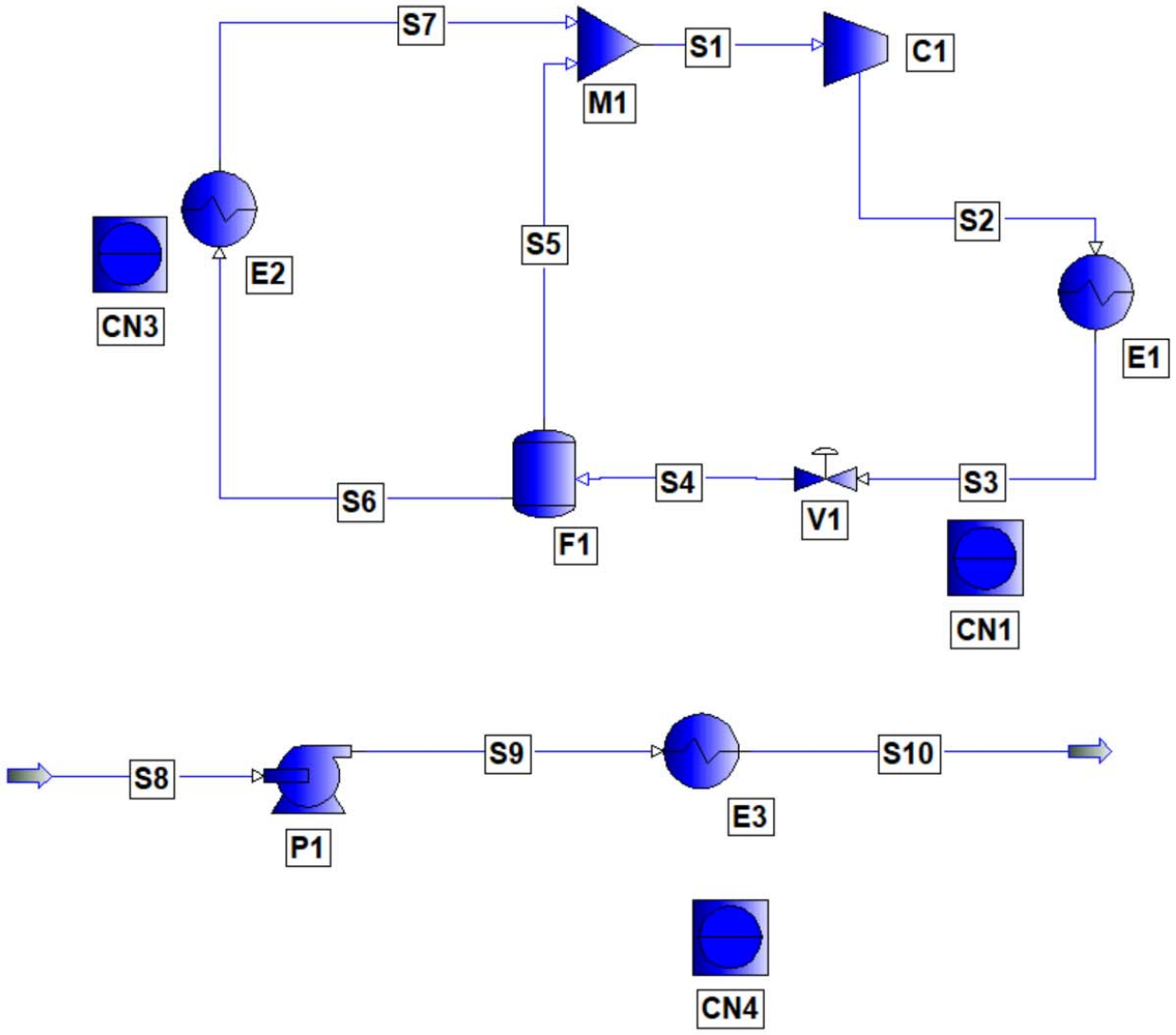
4 Problem Descriptions

Problem Descriptions:

- LNG Feedstock:
  - Typical LNG Composition:
  - LNG supply temperature: -163^{o}C
  - LNG supply pressure: 8.5bar
- Refrigeration Cycle:
  - Evaporator duty: 0.5x10^{6} kcal/h
  - Refrigerant supply temperature: Expander outlet pressure: 1.2 bar
  - 2nd refrigerant:
    - Cooling water supply temperature: 32^{o}C
    - Cooling water return temperature: 40^{o}C
    - Refrigerant temperature at condenser outlet condition: 45^{o}C
- LNG outlet stream temperature:
  - Approach temperature between refrigerant and LNG: 3^{o}C
- Electric power price:
  - 113 Won/kWh

5 Single Refrigeration Cycle

Single Refrigeration Cycle:



Single Refrigeration Cycle: 1) R152

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	3.157
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	5,774.3
5	Total refrigerant circulation rate (kg/hr)	6,706.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	94.3, 66.7
7	Condenser heat duty (10^6 Kcal/hr)	0.5811
8	Cooling water consumptions (Ton/hr)	72.6
9	LNG consumption (Kg/hr)	2,447.7
10	Refrigerant supply temperature (°C)	15.147
11	1 ton/h LNG price (Won/Ton)	4,353.4

$$\frac{(94.3\,\mathrm{kW})}{\left(2,447.7\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=4,353.4원/\mathrm{Ton}$$

Single Refrigeration Cycle: 2) R21

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	3.421
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	8,932.8
5	Total refrigerant circulation rate (kg/hr)	10,342.1
6	Compressor power (kW) & compressor outlet stream temperature (°C)	102.2, 74.9
7	Condenser heat duty (10^6 Kcal/hr)	0.5879
8	Cooling water consumptions (Ton/hr)	73.5
9	LNG consumption (Kg/hr)	2,461.3
10	Refrigerant supply temperature (°C)	12.948
11	1 ton/h LNG price (Won/Ton)	4,692.1

$$\frac{(102.2\,\mathrm{kW})}{\left(2{,}461.3\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=4{,}692.1원/\mathrm{Ton}$$

Single Refrigeration Cycle: 3) R133a

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	3.647
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	10,556.2
5	Total refrigerant circulation rate (kg/hr)	13,164.3
6	Compressor power (kW) & compressor outlet stream temperature (°C)	114.7, 56.2
7	Condenser heat duty (10^6 Kcal/hr)	0.5986
8	Cooling water consumptions (Ton/hr)	74.8
9	LNG consumption (Kg/hr)	2,475.6
10	Refrigerant supply temperature (°C)	10.657
11	1 ton/h LNG price (Won/Ton)	5,235.5

$$\frac{(114.7\,\mathrm{kW})}{\left(2{,}475.6\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=5{,}235.5원/\mathrm{Ton}$$

Single Refrigeration Cycle: 4) R114

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	3.882
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	15,714.5
5	Total refrigerant circulation rate (kg/hr)	21,470.5
6	Compressor power (kW) & compressor outlet stream temperature (°C)	131.5, 45 (W)
7	Condenser heat duty (10^6 Kcal/hr)	0.6131
8	Cooling water consumptions (Ton/hr)	76.6
9	LNG consumption (Kg/hr)	2,491.6
10	Refrigerant supply temperature (°C)	8.130
11	1 ton/h LNG price (Won/Ton)	5,963.8

$$\frac{(131.5\,\mathrm{kW})}{\left(2{,}491.6\,\frac{kg}{h}\right)}\times\frac{(113\text{원})}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=5{,}963.8\text{원}/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 5) R600 (nC_4H_{10})

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	4.335
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	5,476.0
5	Total refrigerant circulation rate (kg/hr)	7,396.8
6	Compressor power (kW) & compressor outlet stream temperature (°C)	147.3, 51.2
7	Condenser heat duty (10^6 Kcal/hr)	0.6267
8	Cooling water consumptions (Ton/hr)	78.3
9	LNG consumption (Kg/hr)	2,512.8
10	Refrigerant supply temperature (°C)	4.055
11	1 ton/h LNG price (Won/Ton)	6,624.0

$$\frac{(147.3\text{kW})}{\left(2{,}512.8\,\frac{kg}{h}\right)}\times\frac{(113\text{원})}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=6{,}624.0\text{원}/\text{Ton}$$

Single Refrigeration Cycle: 6) R3-1-10 (C_4F_{10})

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	4.845
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	22,006.8
5	Total refrigerant circulation rate (kg/hr)	42,642.7
6	Compressor power (kW) & compressor outlet stream temperature (°C)	196.9, 45 (W)
7	Condenser heat duty (10^6 Kcal/hr)	0.6693
8	Cooling water consumptions (Ton/hr)	83.7
9	LNG consumption (Kg/hr)	2,529.0
10	Refrigerant supply temperature (°C)	2.3
11	1 ton/h LNG price (Won/Ton)	8,797.8

$$\frac{(196.9\,\mathrm{kW})}{\left(2{,}529.0\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=8{,}797.8원/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 7) R12B1 ($CBrClF_2$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	4.870
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	15,642.8
5	Total refrigerant circulation rate (kg/hr)	20,375.3
6	Compressor power (kW) & compressor outlet stream temperature (°C)	158.7, 68.1
7	Condenser heat duty (10^6 Kcal/hr)	0.6365
8	Cooling water consumptions (Ton/hr)	79.6
9	LNG consumption (Kg/hr)	2,540.6
10	Refrigerant supply temperature (°C)	0.52
11	1 ton/h LNG price (Won/Ton)	7,058.6

$$\frac{(158.7\,\mathrm{kW})}{\left(2{,}540.6\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=7{,}058.6원/\mathrm{Ton}$$

Single Refrigeration Cycle: 8) R318 (C_4F_8)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	5.623
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	18,369.1
5	Total refrigerant circulation rate (kg/hr)	33,114.0
6	Compressor power (kW) & compressor outlet stream temperature (°C)	208.8, 45.0
7	Condenser heat duty (10^6 Kcal/hr)	0.6796
8	Cooling water consumptions (Ton/hr)	84.9
9	LNG consumption (Kg/hr)	2,555.6
10	Refrigerant supply temperature (°C)	-1.75
11	1 ton/h LNG price (Won/Ton)	9,232.4

$$\frac{(208.8\,\mathrm{kW})}{\left(2{,}555.6\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=9{,}232.4원/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 9) R630 (CH_3NH_2)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	6.641
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	2,587.3
5	Total refrigerant circulation rate (kg/hr)	3,209.3
6	Compressor power (kW) & compressor outlet stream temperature (°C)	174.2, 110.3
7	Condenser heat duty (10^6 Kcal/hr)	0.6497
8	Cooling water consumptions (Ton/hr)	81.2
9	LNG consumption (Kg/hr)	2,566.1
10	Refrigerant supply temperature (°C)	-3.331
11	1 ton/h LNG price (Won/Ton)	7,671.0

$$\frac{(174.2\,\mathrm{kW})}{\left(2{,}566.1\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=7{,}671.0원/\mathrm{Ton}$$

Single Refrigeration Cycle: 10) R31 (CH_2FCl)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	4.845
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	22,006.8
5	Total refrigerant circulation rate (kg/hr)	42,642.7
6	Compressor power (kW) & compressor outlet stream temperature (°C)	196.9, 45.0
7	Condenser heat duty (10^6 Kcal/hr)	0.6693
8	Cooling water consumptions (Ton/hr)	83.7
9	LNG consumption (Kg/hr)	2,529.0
10	Refrigerant supply temperature (°C)	2.30
11	1 ton/h LNG price (Won/Ton)	8,797.8

$$\frac{(196.9\,\mathrm{kW})}{\left(2{,}529.0\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=8{,}797.8원/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 11) R764 (SO_2)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	7.386
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	5,494.5
5	Total refrigerant circulation rate (kg/hr)	6,707.1
6	Compressor power (kW) & compressor outlet stream temperature (°C)	196.7, 161.3
7	Condenser heat duty (10^6 Kcal/hr)	0.6691
8	Cooling water consumptions (Ton/hr)	83.6
9	LNG consumption (Kg/hr)	2,591.8
10	Refrigerant supply temperature (°C)	-7.148
11	1 ton/h LNG price (Won/Ton)	8,575.9

$$\frac{(196.7\,\mathrm{kW})}{\left(2{,}591.8\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=8{,}575.9원/\mathrm{Ton}$$

Single Refrigeration Cycle: 12) R600A (i-C_4H_{10})

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	6.040
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	5,827.4
5	Total refrigerant circulation rate (kg/hr)	8,897.5
6	Compressor power (kW) & compressor outlet stream temperature (°C)	214.6, 52.9
7	Condenser heat duty (10^6 Kcal/hr)	0.6845
8	Cooling water consumptions (Ton/hr)	85.6
9	LNG consumption (Kg/hr)	2,594.3
10	Refrigerant supply temperature (°C)	-7.515
11	1 ton/h LNG price (Won/Ton)	9,347.3

$$\frac{(214.6\,\mathrm{kW})}{\left(2{,}594.3\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=9{,}347.3원/\mathrm{Ton}$$

Single Refrigeration Cycle: 13) R124 ($C_2F_4Cl_2$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	6.700
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	12,961.4
5	Total refrigerant circulation rate (kg/hr)	20,295.4
6	Compressor power (kW) & compressor outlet stream temperature (°C)	221.0, 54.9
7	Condenser heat duty (10^6 Kcal/hr)	0.6900
8	Cooling water consumptions (Ton/hr)	86.3
9	LNG consumption (Kg/hr)	2,598.1
10	Refrigerant supply temperature (°C)	-8.074
11	1 ton/h LNG price (Won/Ton)	9,612.0

$$\frac{(221.0\,\mathrm{kW})}{\left(2{,}598.1\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=9{,}612.0원/\mathrm{Ton}$$

Single Refrigeration Cycle: 14) R245 ($C_3H_3F_5$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	8.038
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	13,003.1
5	Total refrigerant circulation rate (kg/hr)	25,358.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	290.4, 45.0
7	Condenser heat duty (10^6 Kcal/hr)	0.7497
8	Cooling water consumptions (Ton/hr)	93.7
9	LNG consumption (Kg/hr)	2,635.9
10	Refrigerant supply temperature (°C)	-13.556
11	1 ton/h LNG price (Won/Ton)	12,449.3

$$\frac{(290.4\,\mathrm{kW})}{\left(2{,}635.9\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=12{,}449.3원/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 15) R134 ($C_2H_2F_4$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	9.619
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	9,693.7
5	Total refrigerant circulation rate (kg/hr)	16,104.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	283.0, 64.4
7	Condenser heat duty (10^6 Kcal/hr)	0.7434
8	Cooling water consumptions (Ton/hr)	92.9
9	LNG consumption (Kg/hr)	2,665.6
10	Refrigerant supply temperature (°C)	-17.757
11	1 ton/h LNG price (Won/Ton)	11,996.9

$$\frac{(283.0\,\mathrm{kW})}{\left(2{,}665.6\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=11{,}996.9원/\mathrm{Ton}$$

Single Refrigeration Cycle: 16) R40 (CH_3Cl)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	9.845
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	4,951.1
5	Total refrigerant circulation rate (kg/hr)	6,499.6
6	Compressor power (kW) & compressor outlet stream temperature (°C)	271.8, 161.4
7	Condenser heat duty (10^6 Kcal/hr)	0.7337
8	Cooling water consumptions (Ton/hr)	91.7
9	LNG consumption (Kg/hr)	2,683.1
10	Refrigerant supply temperature (°C)	-20.201
11	1 ton/h LNG price (Won/Ton)	12,449.3

$$\frac{(171.8\,\mathrm{kW})}{\left(2{,}683.1\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=7{,}235.4원/\mathrm{Ton}$$

Single Refrigeration Cycle: 17) RE170 (CH_3OCH_3)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	10.163
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	4,525.3
5	Total refrigerant circulation rate (kg/hr)	6,797.6
6	Compressor power (kW) & compressor outlet stream temperature (°C)	284.4, 92.8
7	Condenser heat duty (10^6 Kcal/hr)	0.7446
8	Cooling water consumptions (Ton/hr)	93.1
9	LNG consumption (Kg/hr)	2,688.1
10	Refrigerant supply temperature (°C)	-20.885
11	1 ton/h LNG price (Won/Ton)	11,955.4

$$\frac{(284.4\,\mathrm{kW})}{\left(2{,}688.1\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=11{,}955.4원/\mathrm{Ton}$$

Single Refrigeration Cycle: 18) R152A ($C_3H_2F_4$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	10.586
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	6,415.9
5	Total refrigerant circulation rate (kg/hr)	10,045.9
6	Compressor power (kW) & compressor outlet stream temperature (°C)	295.3, 91.1
7	Condenser heat duty (10^6 Kcal/hr)	0.7539
8	Cooling water consumptions (Ton/hr)	94.2
9	LNG consumption (Kg/hr)	2,690.1
10	Refrigerant supply temperature (°C)	-21.170
11	1 ton/h LNG price (Won/Ton)	12,404.3

$$\frac{(295.3\,\mathrm{kW})}{\left(2{,}690.1\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=12{,}404.3원/\mathrm{Ton}$$

Single Refrigeration Cycle: 19) R134A ($C_2H_2F_4$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	11.604
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	9,701.8
5	Total refrigerant circulation rate (kg/hr)	17,317.8
6	Compressor power (kW) & compressor outlet stream temperature (°C)	327.8, 72.2
7	Condenser heat duty (10^6 Kcal/hr)	0.7819
8	Cooling water consumptions (Ton/hr)	97.7
9	LNG consumption (Kg/hr)	2,698.0
10	Refrigerant supply temperature (°C)	-22.257
11	1 ton/h LNG price (Won/Ton)	13,729.2

$$\frac{(327.8\,\mathrm{kW})}{\left(2{,}698.0\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=13{,}729.2원/\mathrm{Ton}$$

Single Refrigeration Cycle: 20) R1113 (C_2ClF_3)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	11.013
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	11,544.4
5	Total refrigerant circulation rate (kg/hr)	20,704.3
6	Compressor power (kW) & compressor outlet stream temperature (°C)	331.5, 69.5
7	Condenser heat duty (10^6 Kcal/hr)	0.7851
8	Cooling water consumptions (Ton/hr)	98.1
9	LNG consumption (Kg/hr)	2,703.4
10	Refrigerant supply temperature (°C)	-22.991
11	1 ton/h LNG price (Won/Ton)	13,856.4

$$\frac{(331.5\,\mathrm{kW})}{\left(2{,}703.4\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=13{,}856.4원/\mathrm{Ton}$$

Single Refrigeration Cycle: 21) R1234YF ($C_3H_2F_6$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	11.548
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	11,665.2
5	Total refrigerant circulation rate (kg/hr)	25,225.0
6	Compressor power (kW) & compressor outlet stream temperature (°C)	401.6, 55.3
7	Condenser heat duty (10^6 Kcal/hr)	0.8453
8	Cooling water consumptions (Ton/hr)	105.7
9	LNG consumption (Kg/hr)	2,721.4
10	Refrigerant supply temperature (°C)	-25.438
11	1 ton/h LNG price (Won/Ton)	16,675.5

$$\frac{(401.6\,\mathrm{kW})}{\left(2{,}721.4\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=16{,}675.5원/\mathrm{Ton}$$

Single Refrigeration Cycle: 24) R12 (CCl_2F_2)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	10.826
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	12,776.3
5	Total refrigerant circulation rate (kg/hr)	21,693.8
6	Compressor power (kW) & compressor outlet stream temperature (°C)	338.5, 81.5
7	Condenser heat duty (10^6 Kcal/hr)	0.7911
8	Cooling water consumptions (Ton/hr)	98.9
9	LNG consumption (Kg/hr)	2,723.7
10	Refrigerant supply temperature (°C)	-25.751
11	1 ton/h LNG price (Won/Ton)	14,035.6

$$\frac{(338.5\,\mathrm{kW})}{\left(2,723.7\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=14,035.6원/\mathrm{Ton}$$

Single Refrigeration Cycle: 25) R717 (NH_3)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	17.739
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	1,517.3
5	Total refrigerant circulation rate (kg/hr)	2,053.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	353.8, 253.6
7	Condenser heat duty (10^6 Kcal/hr)	0.8042
8	Cooling water consumptions (Ton/hr)	100.5
9	LNG consumption (Kg/hr)	2,753.4
10	Refrigerant supply temperature (°C)	-29.710
11	1 ton/h LNG price (Won/Ton)	14,035.6

$$\frac{(353.8\,\mathrm{kW})}{\left(2{,}753.4\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=14{,}035.6원/\mathrm{Ton}$$

Single Refrigeration Cycle: 26) R218 (C_3F_8)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	14.658
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	19,947.0
5	Total refrigerant circulation rate (kg/hr)	123,759.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	1,121.6, 45.0
7	Condenser heat duty (10^6 Kcal/hr)	1.4644
8	Cooling water consumptions (Ton/hr)	183.1
9	LNG consumption (Kg/hr)	2,776.5
10	Refrigerant supply temperature (°C)	-32.725
11	1 ton/h LNG price (Won/Ton)	12,449.3

$$\frac{(1{,}121.6\,\mathrm{kW})}{\left(2{,}776.5\,\frac{kg}{h}\right)}\times\frac{(113\text{원})}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=45{,}647.7\text{원}/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 27) R161 (C_2H_5F)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	15.410
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	4,953.6
5	Total refrigerant circulation rate (kg/hr)	8,384.3
6	Compressor power (kW) & compressor outlet stream temperature (°C)	399.4, 115.5
7	Condenser heat duty (10^6 Kcal/hr)	0.8434
8	Cooling water consumptions (Ton/hr)	105.4
9	LNG consumption (Kg/hr)	2,782.9
10	Refrigerant supply temperature (°C)	-33.562
11	1 ton/h LNG price (Won/Ton)	16,217.7

$$\frac{(399.4\,\mathrm{kW})}{\left(2,782.9\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=16,217.7원/\mathrm{Ton}$$

Single Refrigeration Cycle: 28) R115 (C_2H_5Cl)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	14.996
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	16,889.0
5	Total refrigerant circulation rate (kg/hr)	53,266.2
6	Compressor power (kW) & compressor outlet stream temperature (°C)	651.4, 50.7
7	Condenser heat duty (10^6 Kcal/hr)	1.0601
8	Cooling water consumptions (Ton/hr)	132.5
9	LNG consumption (Kg/hr)	2,796.3
10	Refrigerant supply temperature (°C)	-35.285
11	1 ton/h LNG price (Won/Ton)	26,323.4

$$\frac{(651.4\,\mathrm{kW})}{\left(2,796.3\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=26,323.4원/\mathrm{Ton}$$

Single Refrigeration Cycle: 29) R22 ($CHClF_2$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	17.242
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	9,069.2
5	Total refrigerant circulation rate (kg/hr)	16,017.5
6	Compressor power (kW) & compressor outlet stream temperature (°C)	441.7, 125.1
7	Condenser heat duty (10^6 Kcal/hr)	0.8798
8	Cooling water consumptions (Ton/hr)	110.0
9	LNG consumption (Kg/hr)	2,811.3
10	Refrigerant supply temperature (°C)	-37.197
11	1 ton/h LNG price (Won/Ton)	17,754.1

$$\frac{(441.7\,\mathrm{kW})}{\left(2{,}811.3\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=17{,}754.1원/\mathrm{Ton}$$

Single Refrigeration Cycle: 30) R290 (C_3H_8)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	15.385
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	4,979.9
5	Total refrigerant circulation rate (kg/hr)	10,158.8
6	Compressor power (kW) & compressor outlet stream temperature (°C)	486.7, 83.5
7	Condenser heat duty (10^6 Kcal/hr)	0.9185
8	Cooling water consumptions (Ton/hr)	114.8
9	LNG consumption (Kg/hr)	2,819.7
10	Refrigerant supply temperature (°C)	-38.258
11	1 ton/h LNG price (Won/Ton)	19,504.6

$$\frac{(486.7\,\mathrm{kW})}{\left(2{,}819.7\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=19{,}504.6원/\mathrm{Ton}$$

Single Refrigeration Cycle: 31) R143A ($C_2H_3F_3$)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	16.244
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	9,226.2
5	Total refrigerant circulation rate (kg/hr)	19,908.6
6	Compressor power (kW) & compressor outlet stream temperature (°C)	492.8, 73.7
7	Condenser heat duty (10^6 Kcal/hr)	0.9237
8	Cooling water consumptions (Ton/hr)	115.5
9	LNG consumption (Kg/hr)	2,862.0
10	Refrigerant supply temperature (°C)	-43.524
11	1 ton/h LNG price (Won/Ton)	19,457.2

$$\frac{(492.8\,\mathrm{kW})}{\left(2{,}862.0\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=19{,}457.2원/\mathrm{Ton}$$

2 phase detection at compressor outlet

Single Refrigeration Cycle: 32) R1270 (C_3H_6)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	18.523
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	4,847.4
5	Total refrigerant circulation rate (kg/hr)	9,926.1
6	Compressor power (kW) & compressor outlet stream temperature (°C)	544.8, 102.4
7	Condenser heat duty (10^6 Kcal/hr)	0.9684
8	Cooling water consumptions (Ton/hr)	121.1
9	LNG consumption (Kg/hr)	2,866.9
10	Refrigerant supply temperature (°C)	-44.117
11	1 ton/h LNG price (Won/Ton)	12,449.3

$$\frac{(544.8\,\mathrm{kW})}{\left(2{,}866.9\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=21{,}473.5원/\mathrm{Ton}$$

Single Refrigeration Cycle: 33) R125 (C_2HF_5)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	22.574
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	12,951.3
5	Total refrigerant circulation rate (kg/hr)	48,400.5
6	Compressor power (kW) & compressor outlet stream temperature (°C)	894.5, 69.0
7	Condenser heat duty (10^6 Kcal/hr)	1.2691
8	Cooling water consumptions (Ton/hr)	158.6
9	LNG consumption (Kg/hr)	2,870.5
10	Refrigerant supply temperature (°C)	-44.560
11	1 ton/h LNG price (Won/Ton)	35,212.9

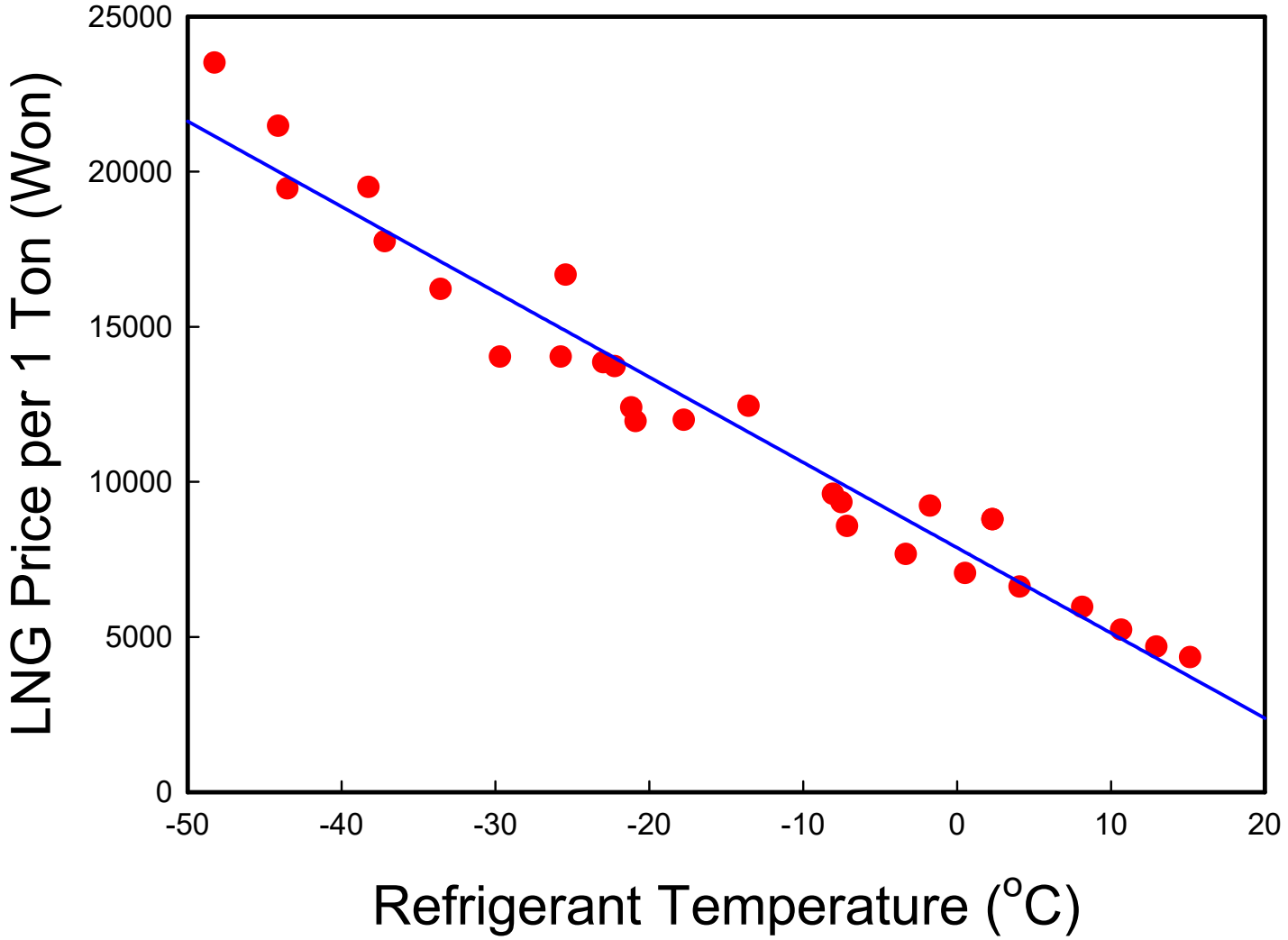
$$\frac{(894.5\,\mathrm{kW})}{\left(2{,}870.5\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=35{,}212.9원/\mathrm{Ton}$$

Single Refrigeration Cycle: 34) R32 (CH_2F_2)

Step	Item	Result
1	Evaporator heat duty (10^6 Kcal/hr)	0.5
2	Compressor discharge pressure (bar)	28.309
3	Expansion valve outlet pressure (bar)	1.200
4	Refrigerant mass flow rate to the evaporator (kg/hr)	5,407.7
5	Total refrigerant circulation rate (kg/hr)	10,102.4
6	Compressor power (kW) & compressor outlet stream temperature (°C)	603.8, 206.1
7	Condenser heat duty (10^6 Kcal/hr)	1.0192
8	Cooling water consumptions (Ton/hr)	127.4
9	LNG consumption (Kg/hr)	2,901.3
10	Refrigerant supply temperature (°C)	-48.261
11	1 ton/h LNG price (Won/Ton)	12,449.3

$$\frac{(603.8\,\mathrm{kW})}{\left(2{,}901.3\,\frac{kg}{h}\right)}\times\frac{(113원)}{(kWh)}\times\frac{h}{h}\times\frac{(10^3\,kg)}{(Ton)}=23{,}516.8원/\mathrm{Ton}$$

LNG Cold Heat Price Applied to Single Refrigeration Cycle:



THANK YOU