Thesis for the Degree of Master of Engineering

Characteristic of Cryogenic Cascade LNG Liquefaction Process

by

Seung-taek Oh

Department of Refrigeration and Air-Conditioning Engineering

The Graduate School

Pukyong National University

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Characteristic of Cryogenic Cascade LNG Liquefaction Process
(초저온 케스케이드 LNG 액화사이클 특성)

Advisor: Prof. Jung-In Yoon

by

Seung-taek Oh

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A dissertation

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Seung-taek Oh

Approved by:

Jong-soo Kum

(Chairman)

Kwang-hwan Choi

(Member)

Jung-in Yoon

(Member)

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NOMENCLATURE

C3	:	Propane	[-]
C2	:	Ethylene	[-]
C1	:	Methane	[-]
P	:	Pressure	[kPa]
V	:	Volume	[m^3]
R	:	Gas constant	[-]
T	:	Temperature	[℃]
G	:	Mass flow rate	[kg/s]
h	:	Enthalpy	[kJ/kg]
Q_e	:	Refrigeration capacity	[MW]
W_c	:	Compressor work	[MW]
COP		Coefficient of performance	[-]
Eva	:	Evaporator	
Comp	:	Compressor	

Subscripts

i	:	Inlet
o	:	Outlet
m	:	Middle
H	:	High
L	:	Low

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Seung-taek Oh

Department of Refrigeration and Air-Conditioning Engineering,
The Graduate School,
Pukyong National University

Abstract

In this paper, several types of natural gas liquefaction process with 2 staged compression cascade processes are designed and simulated to develop the liquefaction process which is the core technology in the Industry of natural gas liquefaction plant. These include the cascade cycle with inter-cooler which is consisted of Propane, Ethylene and Methane cycle. After this, two liquid-gas heat exchangers are applied to between methane and ethylene cycles, and between ethylene and propane cycles. Moreover, the expander is applied to above cascade process. Also, these cycles are compared with basic cascade process. The compressor work and refrigeration capacity of two staged cascade process with inter-cooler are 16.34% and 3.06% lower than that of basic respectively and COP of that is 15.88% higher than that of basic process. Liquid-gas heat exchanger process showed about 18.77% and 6.36% lower compressor work and refrigeration capacity, and 15.27% higher COP than that of basic process. At last, compressor work and refrigeration capacity of expander process is 19.04% and 6.77% lower and COP of that is 15.88% higher than basic cycle respectively. Also, the yield efficiency of LNG has been improved comparing with expander process by 18.99% lower specific power.

초저온 케스케이드 LNG 액화사이클 특성

Seung-taek Oh

Department of Refrigeration and Air-Conditioning Engineering,
The Graduate School,
Pukyong National University

요약

본 연구에서는 천연가스 액화 플랜트 산업에서의 핵심기술인 액화공정을 개발하기 위하여 2단 압축 인터쿨러 방식을 적용한 케스케이드 공정을 시뮬레이션을 통하여 설계하였다. 본 연구에서 수행된 공정들은 프로판, 에틸렌과 메탄 세 가지 사이클로 구성되어 있는 기본 케스케이드 공정을 기초로 하였으며, 이 각각의 사이클에 2단압축 인터쿨러 방식을 적용하였다. 인터쿨러 적용후 액-가스 열교환기 2기를 메탄과 에틸렌 사이클 사이와 에틸렌과 프로판 사이클 사이 각각에 적용하였으며 또한, 위 공정의 천연가스 입구 측에 팽창기를 적용하여 시뮬레이션을 수행 하였다. 위 시뮬레이션 결과를 기본 케스케이드 공정의 성능과 비교 분석 하였다. 2단 압축 인터쿨러 방식을 적용한 케스케이드 공정의 압축 일량과 냉동능력은 기본 케스케이드 공정에 비해 각각 16.34%와 3.06% 감소하였으며, COP는 15.88% 증가하였다. 액-가스 열교환기를 적용한 공정의 압축 일량과 냉동능력은 기본케스케이드 공정에 비해 각각 18.77%와 6.36% 감소하였으며, COP는 15.27% 증가하였다. 위 공정에 팽창기를 적용한 공정의 압축 일량과 냉동능력은 기본 케스케이드 공정에 비해 각각 19.04%와 6.77% 감소하였으며, COP는 15.88% 증가하였다. 팽창기를 적용한 공정의 비에너지는 18.99% 감소로 가장 뛰어난 성능을 나타내었다.

I. Introduction

1. Background

Natural gas from gas field is mixture with methane, ethane, propane, butane, etc., and methane accounts for about 80% of these components, and normal boiling point is about -162℃. Natural gas accounts for 14% of primary energy source in Korea and it is imported and used with the volume of about 26 million ton per annum from overseas. Furthermore, Natural gas is being preferred as the green energy which is colorlessness, odorless and non-toxic and the consumption rate of natural gas is increasing according to the increments of international oil prices. There are LNG(Liquefied Natural Gas) and PNG(Pipe-line Natural gas) types in the transportation of natural gas, and LNG type has more advantages than the existing PNG type for the following reasons. First, LNG type can solve the problem of a long distance transportation by handling liquified natural gas that has smaller 1/600 volume than gaseous natural gas. According to this reason, limited gas field that is far from the market can be developed.

1.1. Liquefaction Process

Fig. 1.1 shows Whole natural gas liquefaction process. Liquefaction process is divided into four processes such as natural gas extracting process from the gas field, pre-treatment process that includes acid gas, dehydration, mercury removal and heavy hydrocarbon removal process, liquefaction process, and storage process. Liquefaction process, it is simulated in this study, is a core technology in the whole process in which pre-treated

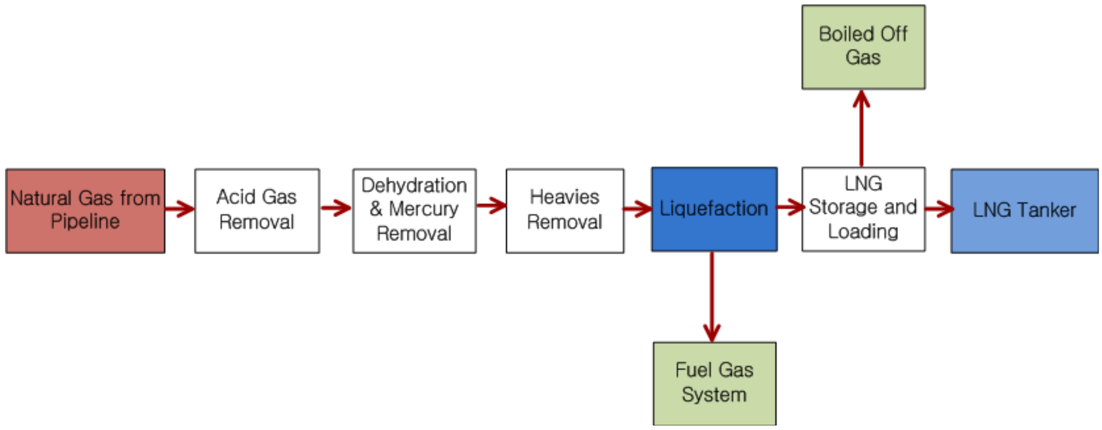


Fig. 1.1 Natural gas liquefaction process

natural gas is cooled to under -162℃ using refrigerator and liquefied. Generated flesh gas in the process and BOG(Boiled Off Gas) in the storage tank are used to fuel of gas turbine to operate compressors and re-liquefaction.

1.2. Trend of LNG Market

According to policy of energy diversification and growing consumption of natural gas, some countries which are not easy to approach to PNG gas field have started to introduce LNG which is one of the natural gas transportation type. However, High cost liquefaction facilities and special facilities such as a transport ship, storage tank and vaporizer are required because of characteristics of liquefaction process. Investment of LNG facilities is increasing as a increment of raw materials' cost and a lack of professionals recently, but investment of transporting chain to transport produced LNG about 400 MTPA (Million Ton Per Annum) required 5~10 billion dollar generally. For these reasons, Natural gas is traded in about 776 BCM (Billion Cubic Meter) that is 26.6% of the natural gas consumption with 2922 BCM, and 22.6% of this, LNG with 226 BCM, is traded and took possession only 7.7% all over the world in 2007. The other hand, 15 countries are producing and 20 countries are introducing LNG about 171 million ton except existing producer according as Equatorial Guinea and Norway launched to produce LNG after 2007. The amount of LNG importation in Asia accounts for nearly 66% of total amount of importation around East asia 3 countries(Japan, Korea, Taiwan) which is not easy to approach the gas field of PNG type, and supply of LNG from Middle East and Pacific area accounts for 65% of this. Hereafter, the advent of swing producing district which is located in the Middle East such as Qatar and a source of supply such as North America will be expected to improve LNG market to be globalization to promote

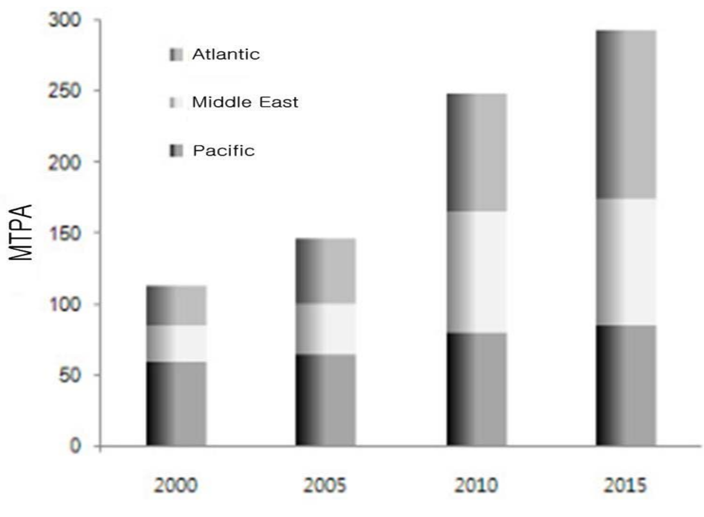


Fig. 1.2 Prospect of LNG supply

revitalization of financial transaction and short term transaction around LNG producing district. Prospect of LNG supply all over the world is shown in Fig. 1.2. According to Wood Mackenzie, supply ability of LNG supply projects which are in operation or under construction will be expected to increase 100 million ton rapidly from 2007 with 177 million ton to 2012 with 270 million ton, and three countries, the Pacific, the Middle East and the Atlantic, will be gotten ability of LNG supply about 1/3 each of whole LNG supply. In the Pacific area, new liquefaction plants are being operated after 2008. According to this, ability of LNG supply will be increased up to 30%, and also. LNG supply ability of the Atlantic area is being on the steady increase as advent of new LNG producer, Egypt, Equatorial Guinea, Norway and etc.

1.3. Trend of LNG Plant Market

Natural gas liquefaction industry has been in the spotlight recently as a higher value-added industry. However, some developed companies monopolize the liquefaction plant market, so developing company is in the difficult situation to get into the market of LNG plant. Market trends of LNG liquefaction process are shown in Fig. 1.3 and 1.4. Japan(JGC and Chiyoda) and the U.S.(KBR and Betchtel) occupy about 97% in the LNG plant market. In the patent, the U.S. occupies about 80% mostly. Korea also occupy about 1.1%, but it has not great influence on this industry. A review of patent trend the U.S. is devoting to technique of liquefaction process and Japan and France are doing pre-treatment process, and Korea and German are doing storage process.

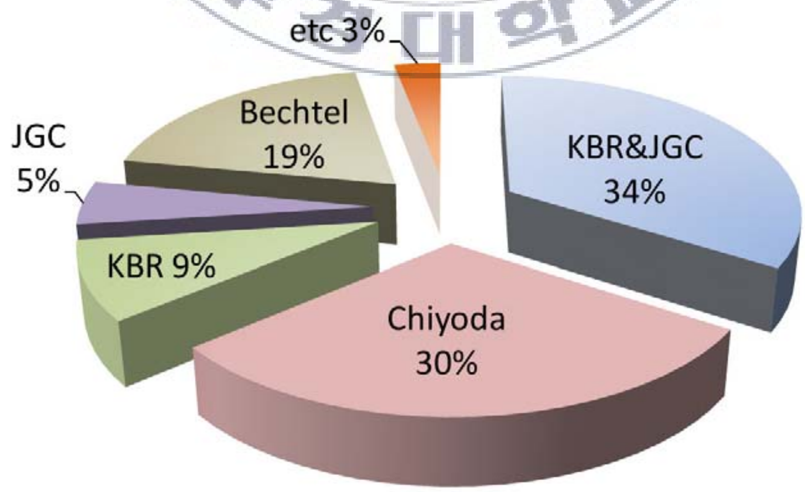


Fig. 1.3 Market share LNG plant EPC

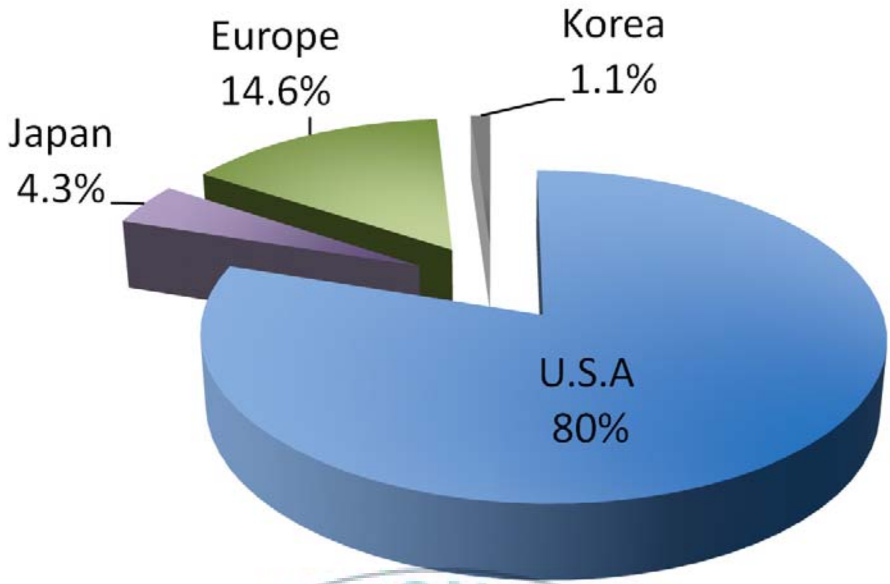


Fig. 1.4 Share of patents

2. Previous Studies

The researches and developments are started in 1960s. Shell company analyzed strengths and weaknesses of cascade process and expansion process using mixed refrigerant and nitrogen through the simulation, D. L. Andress of Phillips company described about development of Optimized cascade process, Kikkawa et al. simulated mixed refrigerant liquefaction process using pre-cooing loop and expander with CHEM CADⅢ software, Terry et al. analyzed and compared representative liquefaction process with Hysys software, Wen-Sheng Cao et al. simulated liquefaction process using refrigerant which mixed nitrogen and methane with Hysys software, and then compared performances with mixed refrigerant liquefaction process. In the Korea, Yoon et al. simulated cascade process with Hysys software, and then offered basic data to this research.

3. Objective of Research

Independent licenser of liquefaction process and development of EPC (Engineering Procurement and Construction) technique are required to secure the competitive in the world market of LNG plant as the higher value-added industry. In this research, Cascade process which is one of representative liquefaction process is simulated with applying several cases and analyzed characteristics of performance to offer basic data of liquefaction process development.

II. Simulation Methods

1. Basic Cascade Liquefaction Process

In this research, cascade process which is the beginning of liquefaction process plant is simulated. Schematic diagram of basic cascade process is shown in the Fig. 2.1. This process cool natural gas gradually using three kinds of pure refrigerants (propane, ethylene, methane). Air-cooled cooler is applied as a condenser of propane cycle, but it is applied as a pre-cooler in ethylene and methane cycles. Each refrigerants is cooled to -40℃ in this cooler and ethylene is condensed in the propane evaporator and methane is condensed in the ethylene evaporator. Natural gas is cooled to -40℃ in the propane evaporator, then cooled to -95℃ in the ethylene evaporator. Finally, natural gas is cooled to -160℃ in the methane evaporator by stages.

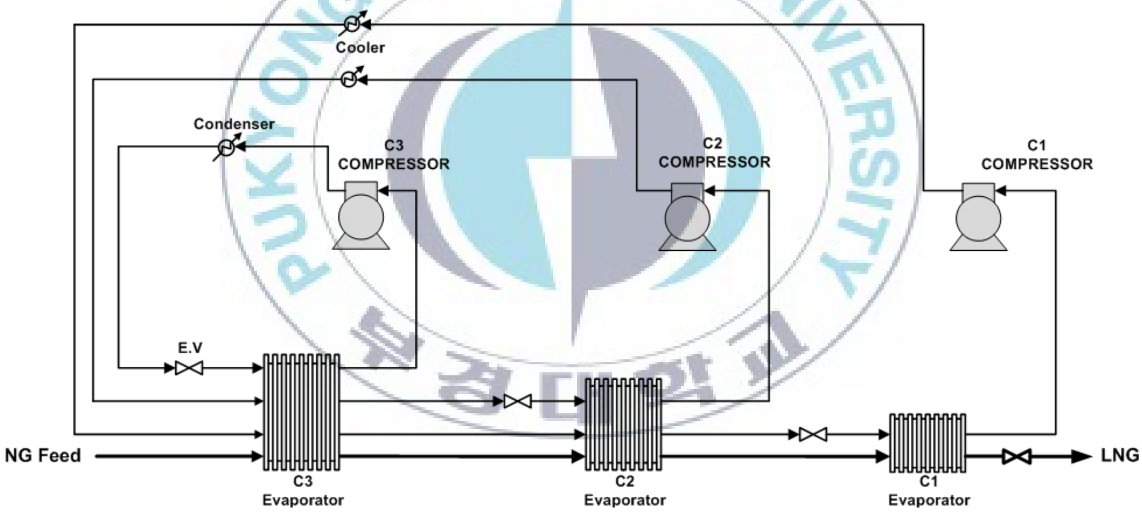


Fig. 2.1 Schematic diagram of basic cascade process

2. Basic Concept of Research

Two staged compression type is applied to basic cascade in this simulation. There are two concept of two staged compression type such as type of 2 stage compression direct expansion and 2 stage compression 2 stage expansion. Schematic diagram of these concepts are shown in Fig. 2.2 and 2.3. In the case of 2 stage compression direct expansion type, there is a inter-cooler, and bypassed refrigerant from condensed main refrigerant supercool main refrigerant in this cooler. Evaporated gaseous refrigerant which has low pressure and temperature from the inter-cooler is mixed with gaseous refrigerant from outlet of 1st compressor and flow into 2st compressor, and this prevents superheating compression. As a result, refrigeration effect per refrigerant mass flow rate increases by decrement of expansion valve outlet quality according to increment of supercooling. In the other case, two staged compressor two staged expansion type, there are two expansion valves. Condensed refrigerant is expanded 1st expansion valve and flow into the separator, then flesh gas and liquefied refrigerant are separated. Separated flesh gas is mixed with gaseous refrigerant from outlet of 1st compressor and flow into 2st

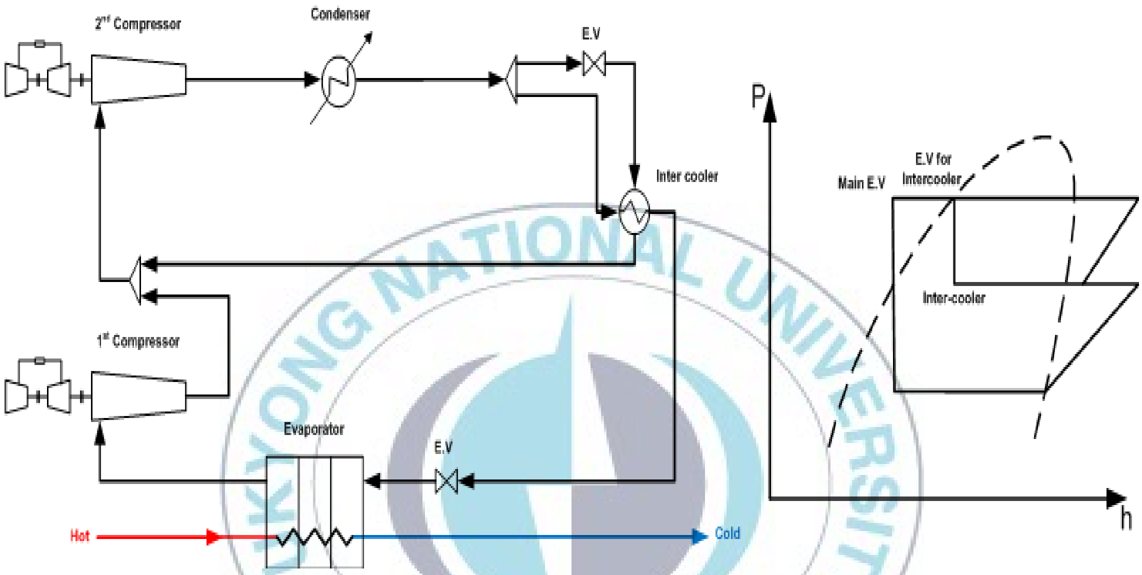


Fig. 2.2 Schematic and P-h diagram of 2 stage compression direct expansion

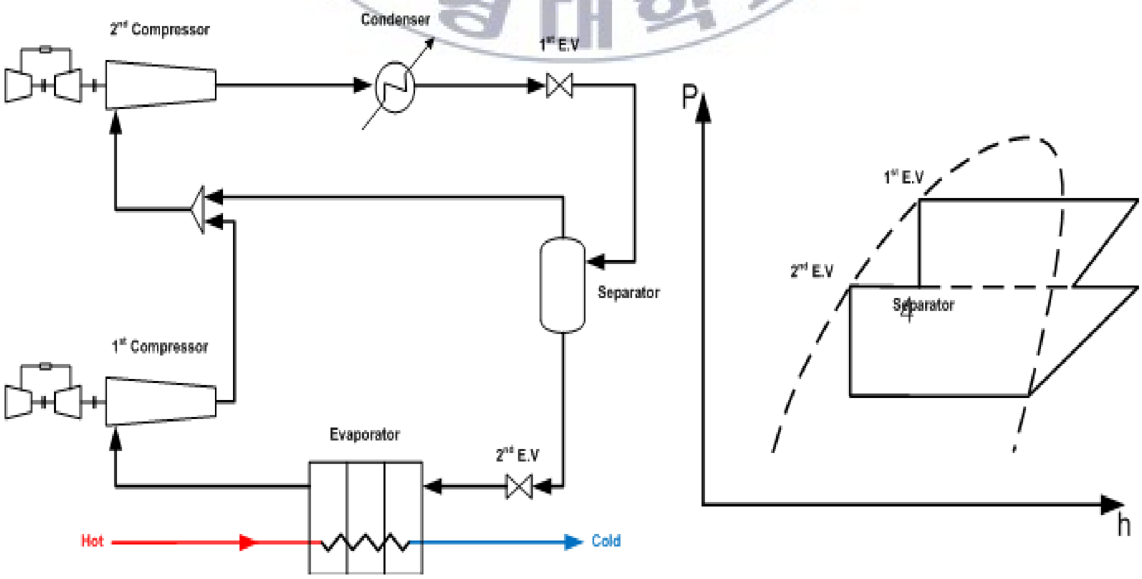


Fig. 2.3 Schematic and P-h diagram of 2 stage compression 2 stage expansion

compressor, and this also prevents superheating compression. Liquefied refrigerant from the separator is expanded again in the 2st expansion valve and flow into evaporator, then it is evaporated. Also, in this case, refrigeration effect per refrigerant mass flow rate increases by decrement of expansion valve outlet quality according to two staged expansion.

In this research, cascade liquefaction process is simulated using two staged direct expansion with inter-cooler.

3. Equations

Two kinds of main equations are used for the liquefaction simulation because natural gas is mixed with methane, ethylene, propane, butane and etc. The Peng-Robinson equation of state applies functionality to some specific component-component interaction parameters, which can be used in the calculation of the phase equilibrium. The Lee-Kesler-Plocker equation is an accurate general method for non-polar substances and mixtures, which can be used in the calculation of enthalpy and entropy of mixed components. Peng-Robinson equation is shown in Fig. 2.1 and 2.2, Lee-Kesler-Ploker equation is shown in Fig. 2.3.

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)+b(V-b)} \tag{2.1}$$

$$a = \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j (a_i a_j)^{0.5}(1-k_{ij})$$

$$b = \sum_{i=1}^{N} x_i b_i$$

It is rewritten by equation (2.2)

$$Z^3 - (1-B)Z^2 + (A-2B-3B^2)Z - (AB-B^2-B^3) = 0 \tag{2.2}$$

$$A = \frac{aP}{(RT)^2} \qquad B = \frac{bP}{RT}$$

where Z is a constringent factor, A and B are the coefficients relating to the gas state parameters.

The Lee-Kesler-Plocker equation is an accurate general method for non-polar substances and mixtures, which can be used in the calculation of enthalpy and entropy of mixed components.

$$Z = Z^{(0)} + \frac{w}{w^{(r)}}(Z^{(r)} - Z^{(0)}) \tag{2.3}$$

where ω is an acentric factor, o and r denote the relevant parameters of simple and reference liquids.

III. Simulation

1. Two Staged Cascade Process using Inter-cooler

First of all, basic cascade process is simulated, using type of two staged compression with inter-cooler. Fig. 3.1 shows schematic diagram of this simulation. In the each cycle, type of two staged compression and inter-coolers are applied. Quality of evaporator outlet and the one of condenser outlet are set 1 and 0 respectively, Δt between of cooling materials and cooled materials which except natural gas is set 5℃. Capacity of all of processes is designed 5MTPA (Million Ton Per Annum) in this research, and conditions of simulation is shown in the table 3.1. Feed gas is assumed pre-treated natural gas which has 5000kPa and 32℃ from the Nigeria gas field, and composition of feed gas is shown in the table 3.2.

Table 3.1 Simulation conditions

Feed gas mass flow rate	[kg/s]	172.4
Liquefaction ratio	[%]	92
Liquefaction temperature	[℃]	-160.1
Evaporator outlet pressure	[kPa]	120
Air cooler outlet temperature	[℃]	40
Evaporator pressure drop	[kPa]	50
Air cooler pressure drop	[kPa]	25

Table 3.2 Composition of Feed gas

Composition	Mole fraction [%]
Nitrogen	0.007
Methane	0.820
Ethane	0.112
Propane	0.040
i-Butane	0.012
n-Butane	0.009
Total	1

2. Two Staged Inter-cooler Cascade using Liquid-gas Heat Exchanger

In this simulation, liquid-gas heat exchangers are applied on the suggested two staged compression inter-cooler cascade process in the result 4.1. At first one heat exchanger is applied between of methane and ethylene cycles, then gaseous methane which has high pressure and temperature from the outlet of high stage compressor is cooled with liquefied ethylene which has low pressure and temperature from the outlet of inter-cooler. Further more, one more heat exchanger is applied between of ethylene and propane on previous process, then gaseous ethylene which has high pressure and temperature from the outlet of high stage compressor is cooled with liquefied propane which has low pressure and temperature from the outlet of inter-cooler. Conditions of simulation is same as the table 3.1, and schematic diagram of this simulation is shown in the Fig. 3.2.

3. Two Staged Inter-cooler Cascade using Expander

In this simulation expander is applied on the suggested process in the result 4.3. Fresh natural gas which is extracted at high pressure as 5000 kPa from the gas field, but LNG is stored at almost atmosphere pressure as 103.3 kPa. Therefor, expander is applied on the natural gas line before cooled to improve efficiency of process by reducing pressure drop in a progress. Also, conditions of simulation is same as the table 3.1, and schematic diagram of this simulation is shown in the Fig. 3.3.

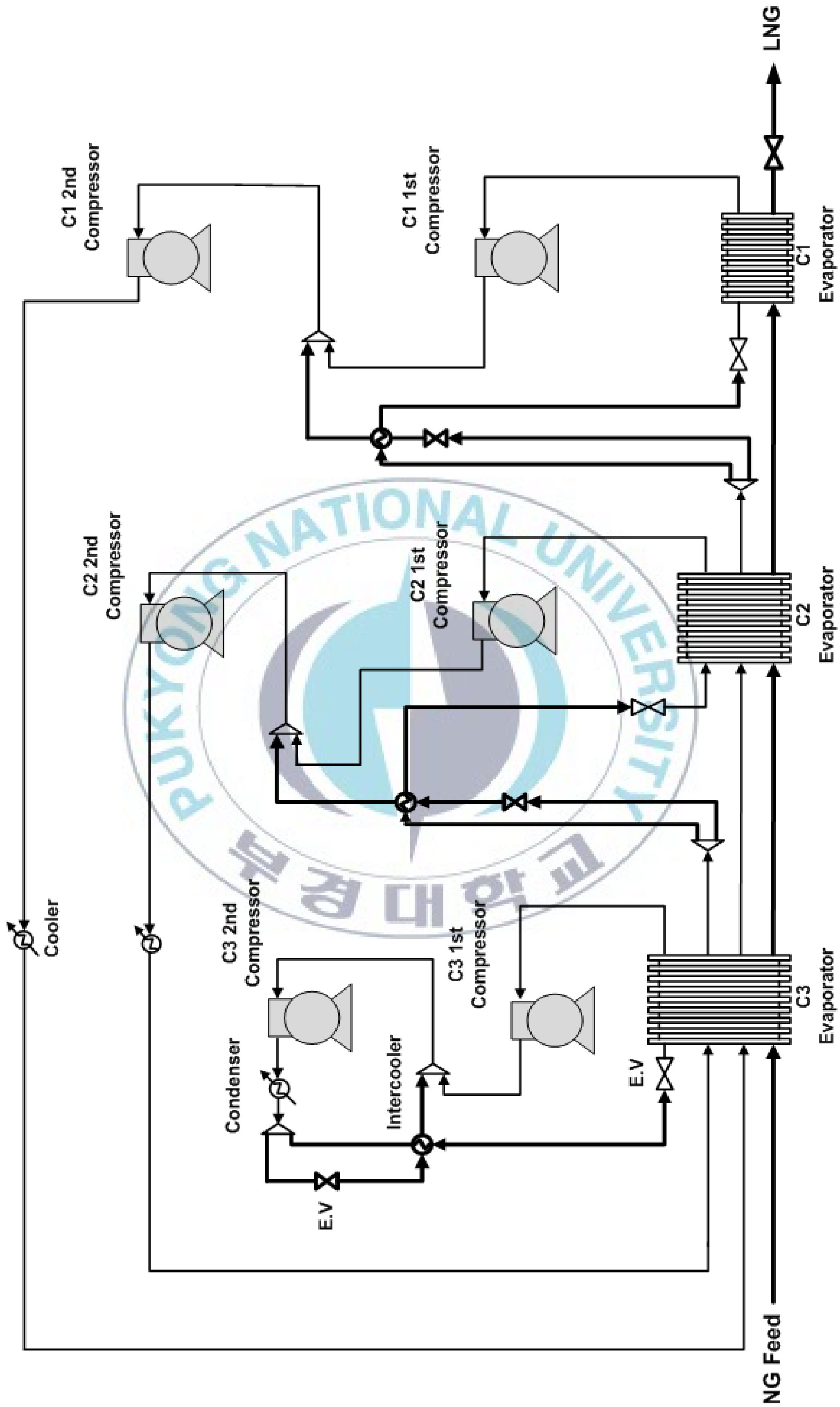


Fig. 3.1 Schematic diagram of 2 staged cascade process using inter-cooler

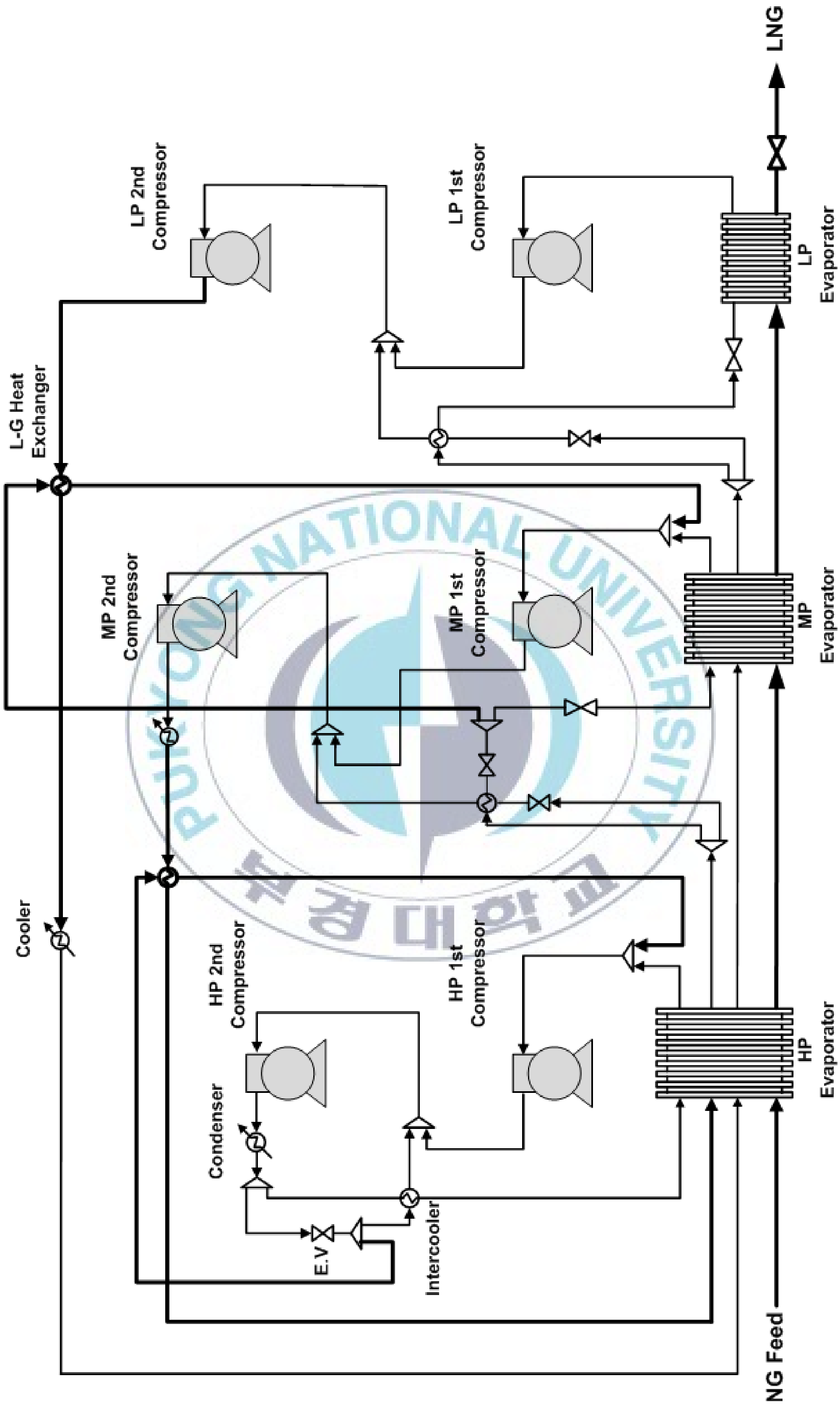


Fig. 3.2 Schematic diagram of 2 Staged Inter-cooler Cascade using Liquid-Gas Heat Exchanger

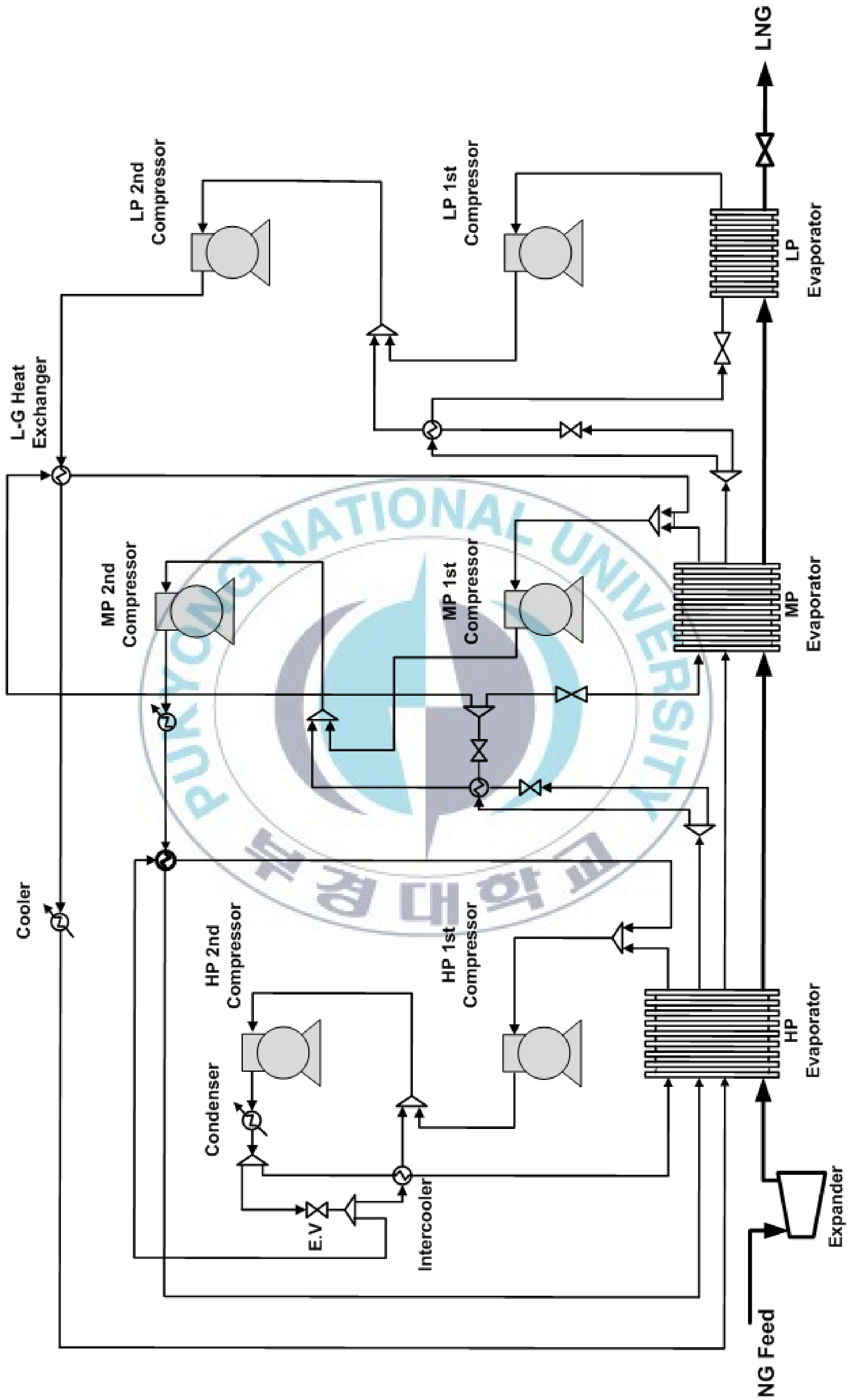


Fig. 3.3 Schematic diagram of 2 Staged Inter-cooler Cascade using Expander

IV. Results and Discussions

1. Two staged Cascade using Inter-cooler

It is assumed that middle pressure and the one of inter-cooler outlet at a bypass side are same, and simulated. Above all, inter-cooler is applied from upper cycle to prove validity of applying of inter-cooler. In this simulation, compression work, power consumption, is the most important one in the liquefaction process, so performance is analyzed more focusing on COP than liquefaction ratio.

Equations which are used to calculate performances are shown in following Equation(4.1) ~ Equation(4.5).

$$Q_e = G \cdot (h_{Eva,o} - h_{eva,i}) \qquad \text{Equation(4.1)}$$

$$W_c = G \cdot (h_{Comp,o} - h_{Comp,i}) \qquad \text{Equation(4.2)}$$

$$COP = \frac{Q_e}{W_c} \qquad \text{Equation(4.3)}$$

$$Specific\,Power = \frac{W_c}{LNG_{\mathrm{Pr}oduct}} \qquad \text{Equation(4.4)}$$

$$\mathrm{Pr}oductivity = \frac{LNG_{\mathrm{Pr}oduct}}{W_c} \qquad \text{Equation(4.5)}$$

Equation(4.6) is used to set a middle pressure.

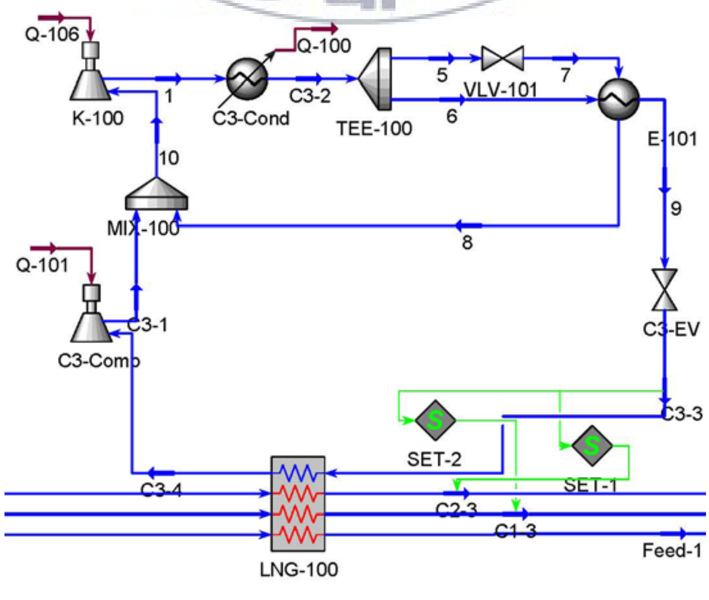
$$P_m = \sqrt{P_H \cdot P_L} \qquad \text{Equation(4.6)}$$

1.1. Propane Cycle using Inter-cooler

At first, inter-cooler is applied in the propane cycle which has a dominating effect on the whole process because that ethylene is condensed and methane is precooled, moreover natural gas is cooled in this cycle. In this process, as middle pressure is dropped, temperature of main refrigerant can be cooled to lower temperature, but bypass refrigerant flow rate which flows into inter-cooler is increased to get the same degree of supercooling according to increment of its quality. As a result, main refrigerant flow rate is increased and it influences compressor work. The other side, according to rise of middle pressure, a degree of suprecooling is decreased, but larger amount of refrigerant can be cooled by quality decrement of bypass refrigerant flow rate which flows into inter-cooler. Design simulation of middle pressure is done because middle pressure and supercooling have like these correlations, and compressor work, refrigeration capacity, COP and liquefaction rate are compared and analyzed. Fig. 4.1 shows process diagram of propane cycle in the practical simulation. Some of liquefied refrigerant which has higher pressure and temperature are bypassed and expanded to middle pressure in the sub-expansion valve and then evaporated in the inter-cooler. According to this evaporating, main refrigerant is precooled and flows into evaporator. As a result, refrigeration effect is increased as refrigerant quality of main expansion valve outlet is decreased by increment of a degree of supercooling.

Variation of performances as bypass flow rate in each pressure is shown in Fig. 4.2. In the compressor work, as middle pressure is dropped, degree of supercooling is increased and compressor work is decreased, however, compressor work is increased from under 500kPa. This is because of overheating compression which is caused by decrement of main refrigerant to evaporator by increment of bypass flow rate. Also, the error of temperature cross that cooled material is cooled to lower temperature than boiling temperature of cooling material is shown from larger than greatest bypass ratio. Compressor work of 500 kPa of middle pressure, 26% of bypass ratio and 600 kPa of middle pressure, 23% of bypass ratio is shown lowest value with 869.355 MW.

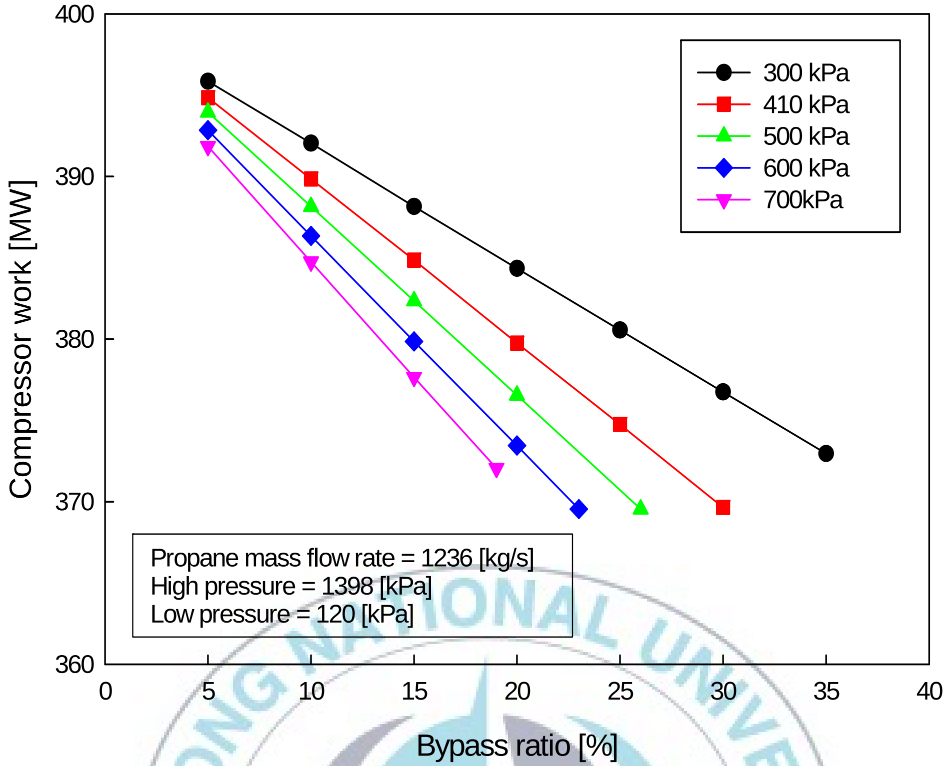
In the refrigeration capacity, it increases as middle pressure drops, but decreases from under 600 kPa. This is because, refrigeration effect is increased by increment of supercooling until 600 kPa, but main refrigerant flow rate which flows into evaporator is more decreased than enhancement effect of refrigeration effect by increment of supercooling from under 600 kPa. Refrigeration capacity of 600 kPa, 23% is shown



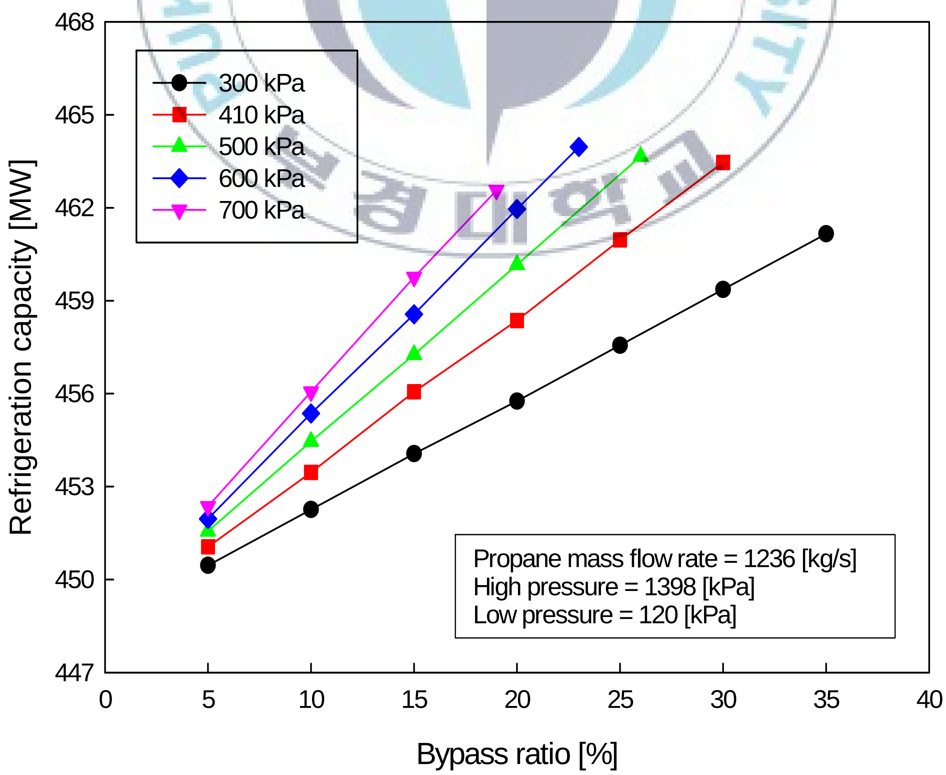
4.1 Simulation design of propane cycle

highest value with 369.55 MW.

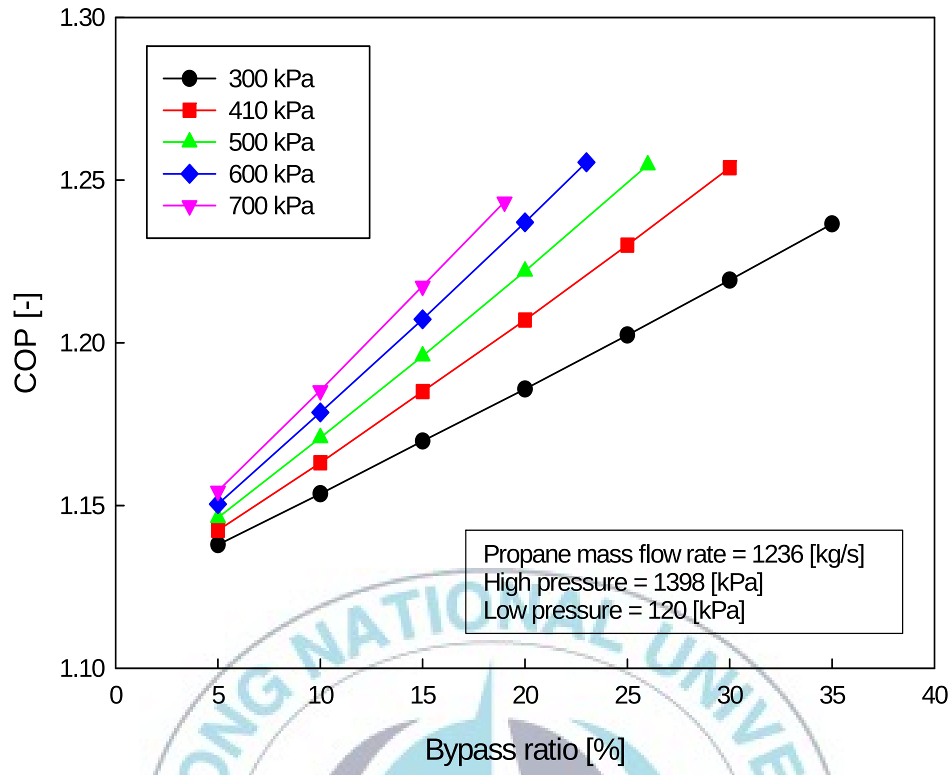
Also, COP and liquefaction ratio at 600 kPa and 23% are shown highest values with 1.26 and 92.96%. For these reasons, middle pressure and bypass ratio are set 600 kPa and 23% to standard conditions of propane cycle. Liquefaction ratio is higher than target of 92%, so it is adjusted to 92% and then one more inter-cooler is applied to ethylene cycle in the following simulation.



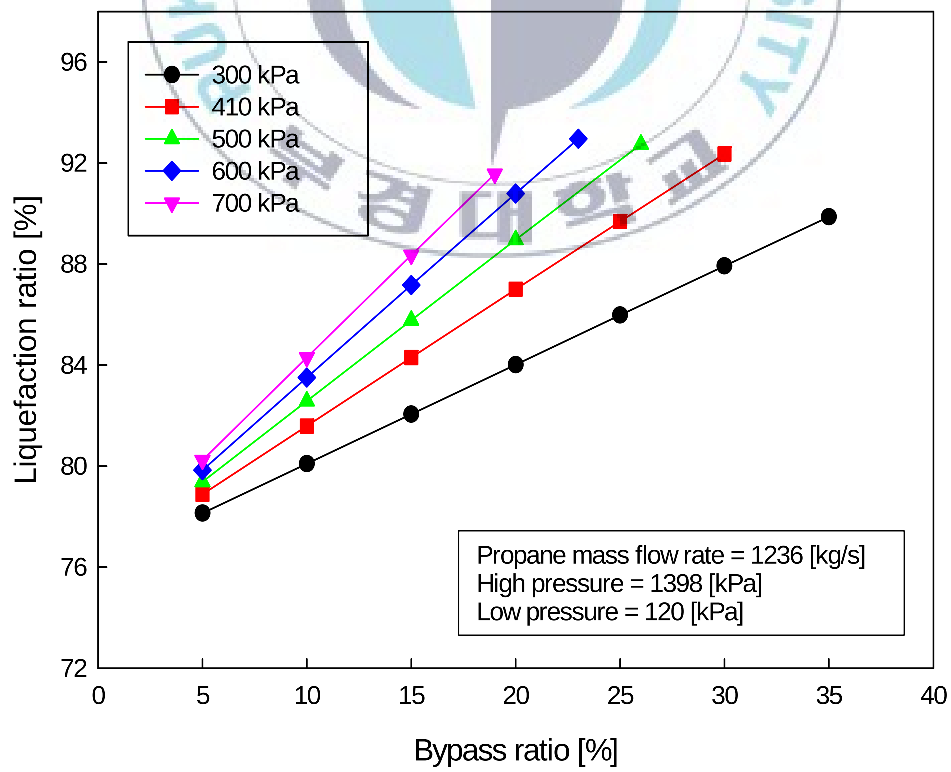
a) Comparison of compressor work as a bypass ratio



b) Comparison of refrigeration capacity work as a bypass ratio



c) Comparison of COP as a bypass ratio

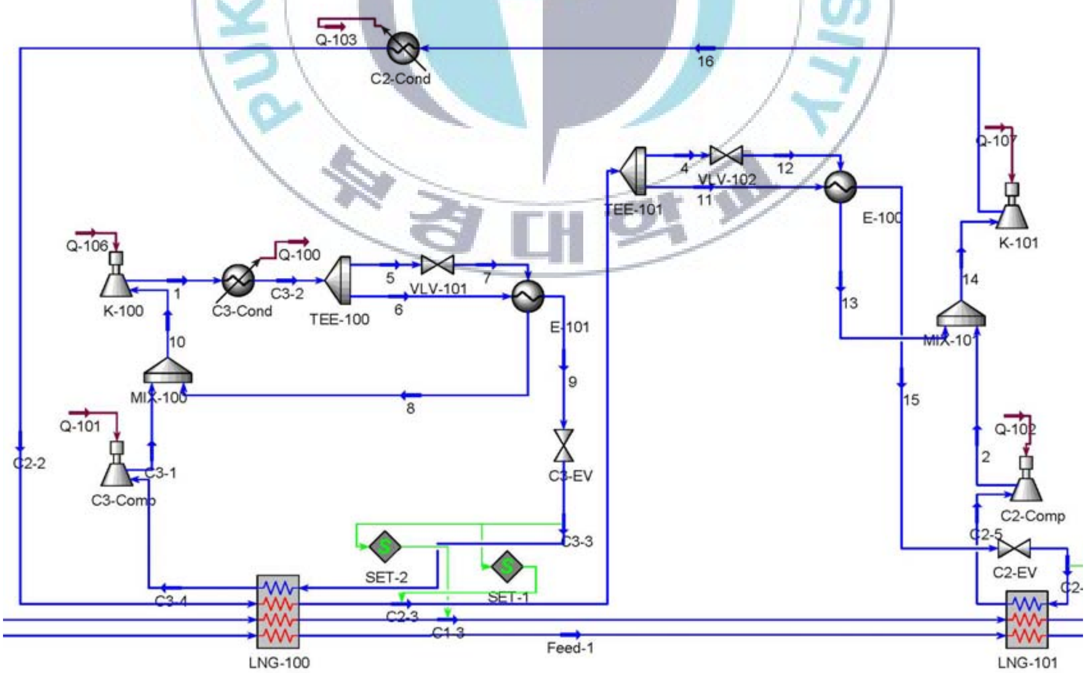


d) Comparison of Liquefaction ratio as a bypass ratio

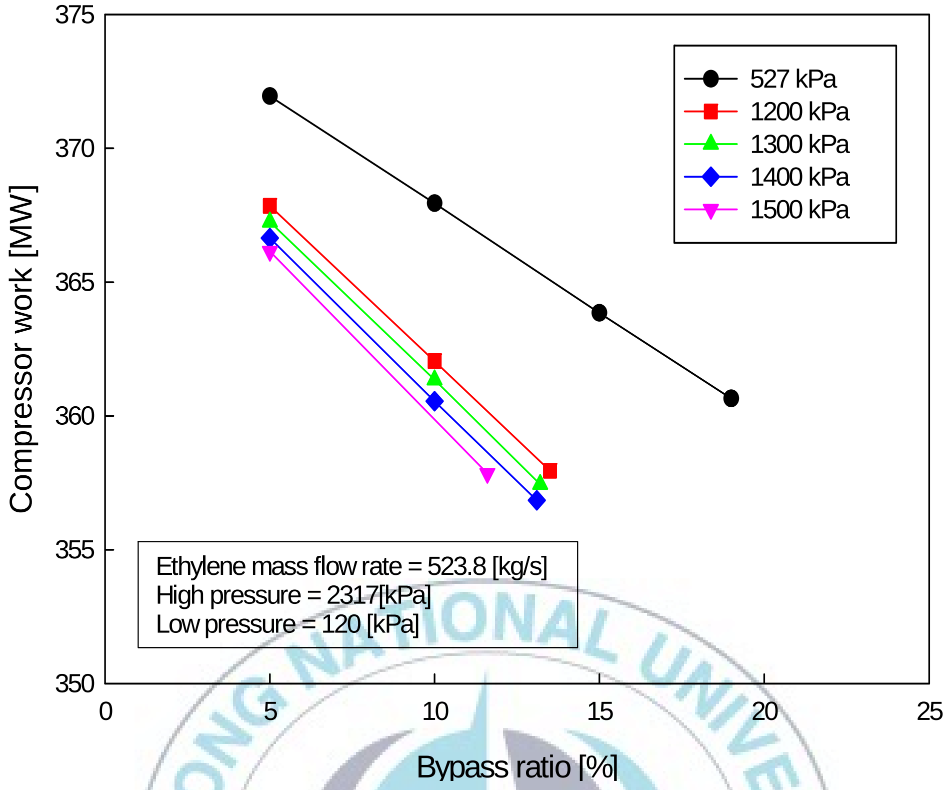
4.2 Performances of modified propane cycle

1.2. Ethylene Cycle using Inter-cooler

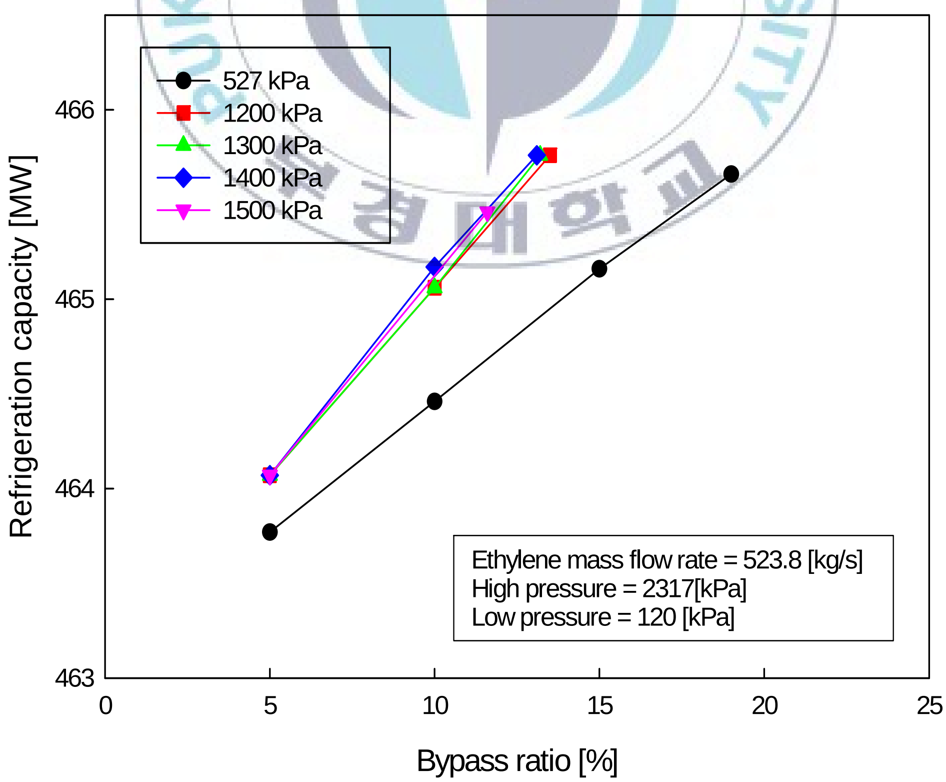
Two staged compression type using inter-cooler is applied to ethylene cycle on the above simulation. At first, 527 kPa of middle pressure which is calculated with Equation(4.6) is inputted and simulation was done, but performance has lower value as shown in Fig. 4.4. For this reason, other level of pressure which shows higher performances than 527 kPa is inputted and simulated. Fig. 4.3 shows process diagram of propane and ethylene cycles in the practical simulation. Also, in this simulation, the error of temperature cross that cooled material is cooled to lower temperature than boiling temperature of cooling material is shown from larger than presented bypass ratio in the result, so performances are compared and analyzed in rages that error of temperature cross is not occurred. In Fig. 4.4, Compressor work of 1400 kPa and 13.1% shows lowest value with 356.85 MW, refrigeration capacity of 1200 kPa, 13.5% and 1300 kPa, 13.2% is shown highest value as 465.76 MW. COP and liquefaction ratio of 1400 kPa and 13.1% are shown highest value as 1.31 and 94.94% in the tree cases. Liquefaction ratio is higher than target of 92%, so it is adjusted to 92% and set to standard condition of ethylene cycle.



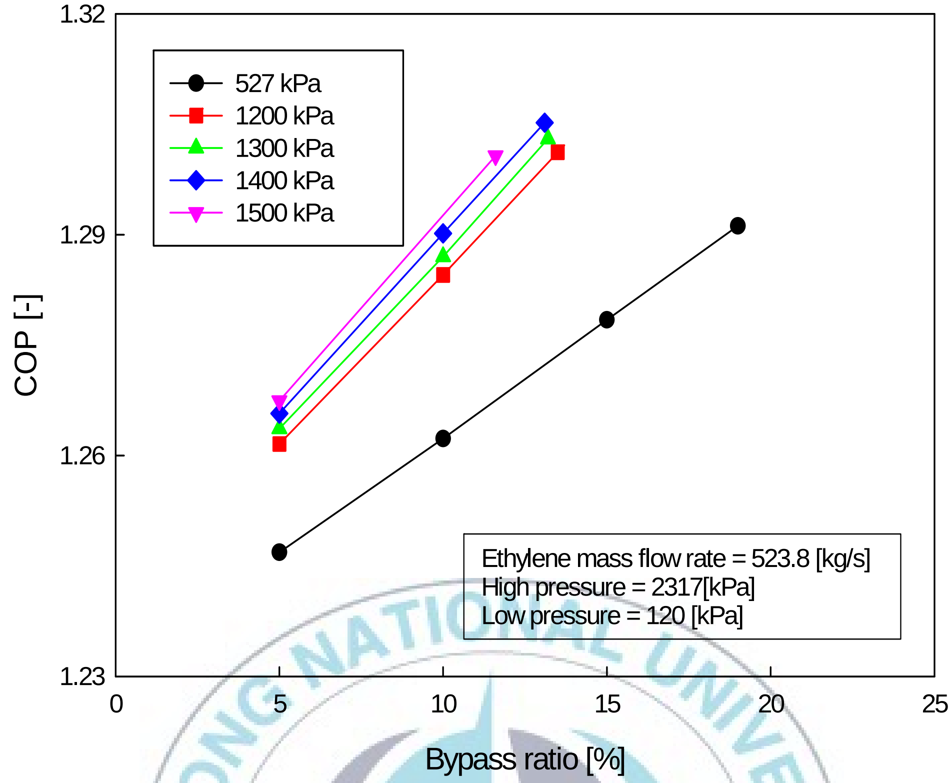
4.3 Simulation design of propane and ethylene cycle



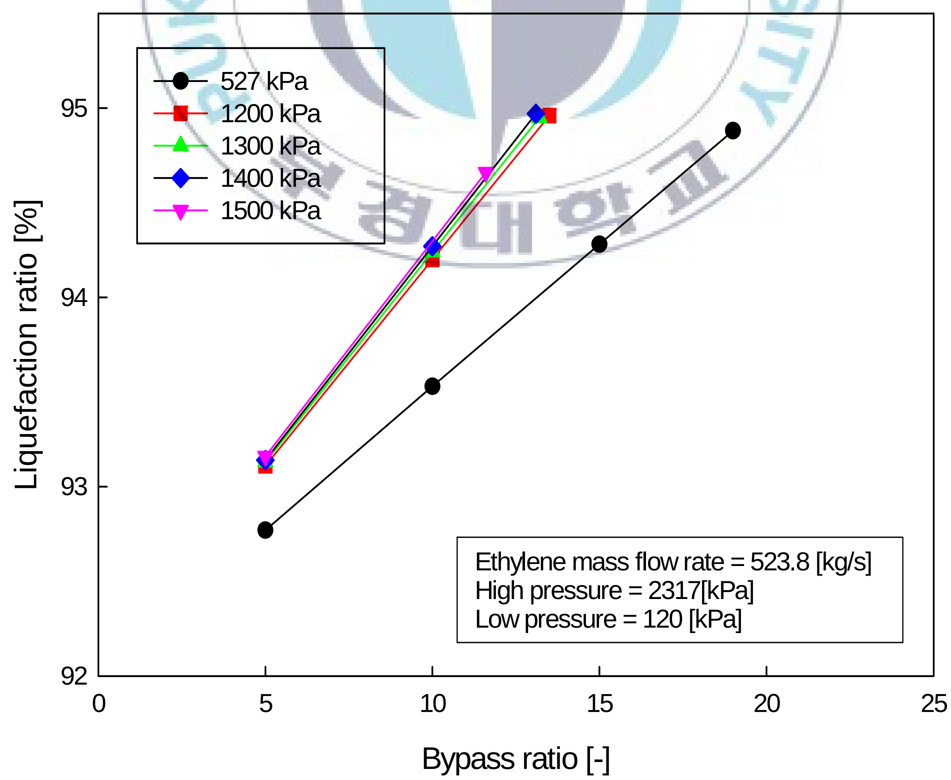
a) Comparison of compressor work as a bypass ratio



b) Comparison of refrigeration capacity work as a bypass ratio



c) Comparison of COP as a bypass ratio

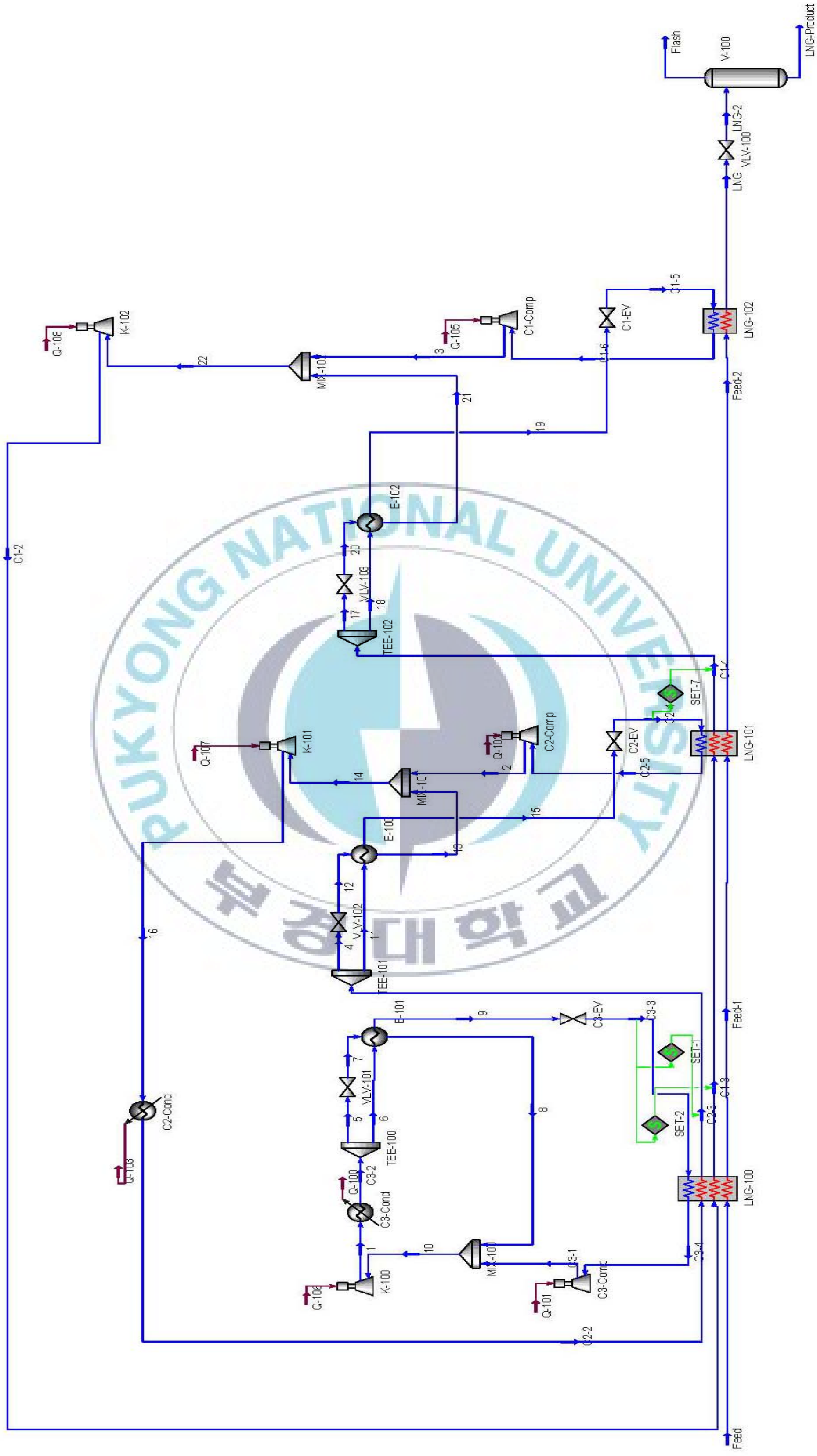


d) Comparison of Liquefaction ratio as a bypass ratio

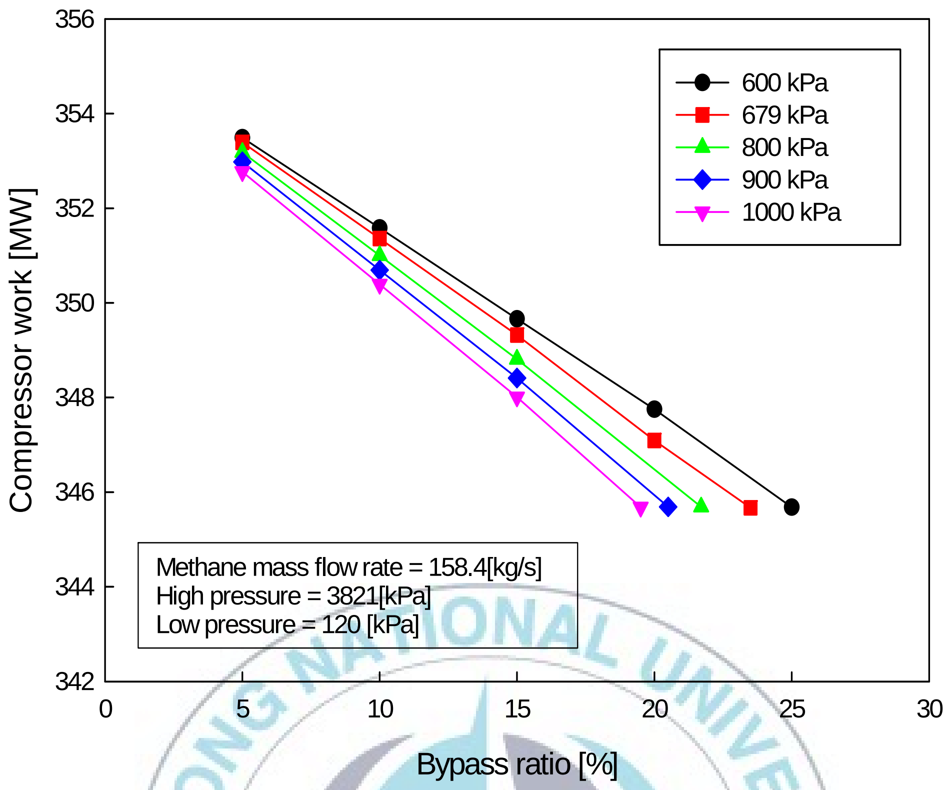
4.4 Performances of modified Ethylene cycle

1.3. Methane Cycle using Inter-cooler

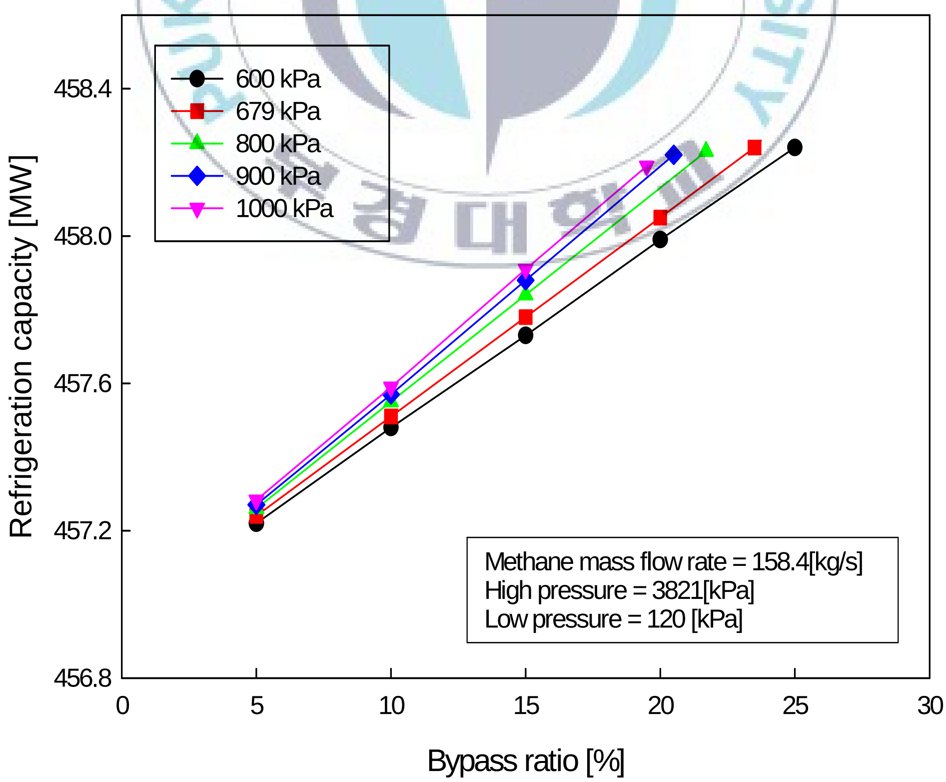
Two staged compression type using inter-cooler is applied to methane cycle on the above simulation. Process diagram of whole cycle in the practical simulation is shown in Fig. 4.3. At first, 679 kPa of middle pressure which is calculated with Equation(4.6) is inputted and simulation is done. Result is shown in Fig. 4.6. All performances are shown similar values, but compressor work, refrigeration capacity, COP of 679 kPa and 23.5% are shown highest performances as 345.67 MW, 458.24 MW and 1.33. In this condition, liquefaction ratio, 94.96% shows higher value than targeted 92%, so it is adjusted to 92% and then performances of whole liquefaction process is analyzed in Result 1.4.



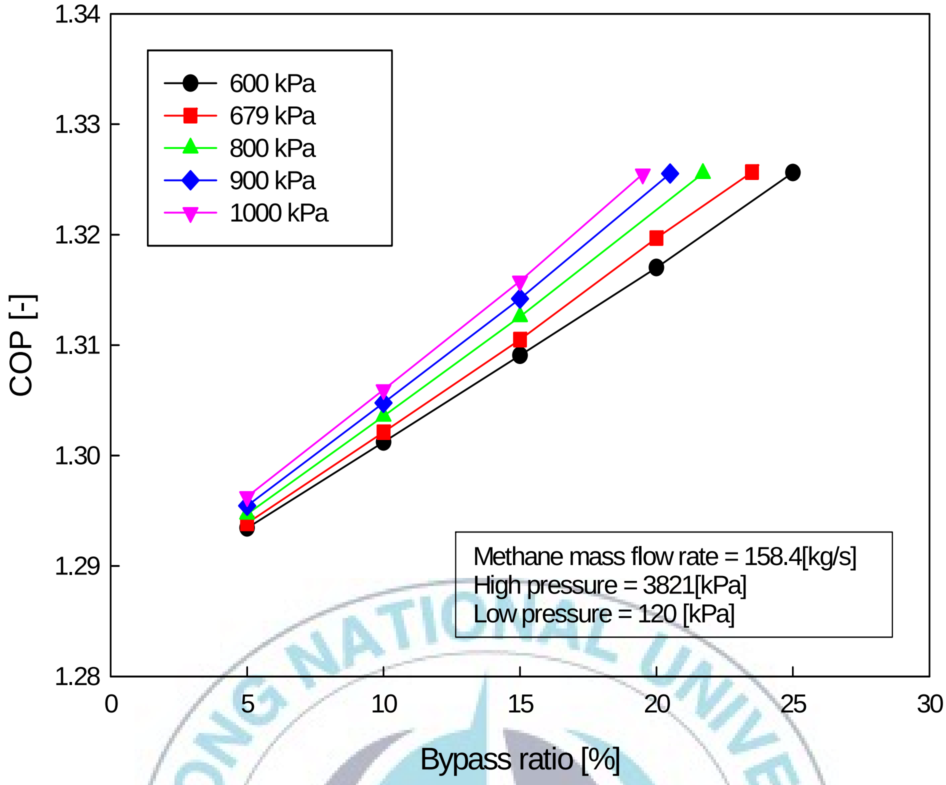
4.5 Simulation design of propane and ethylene and methane cycle



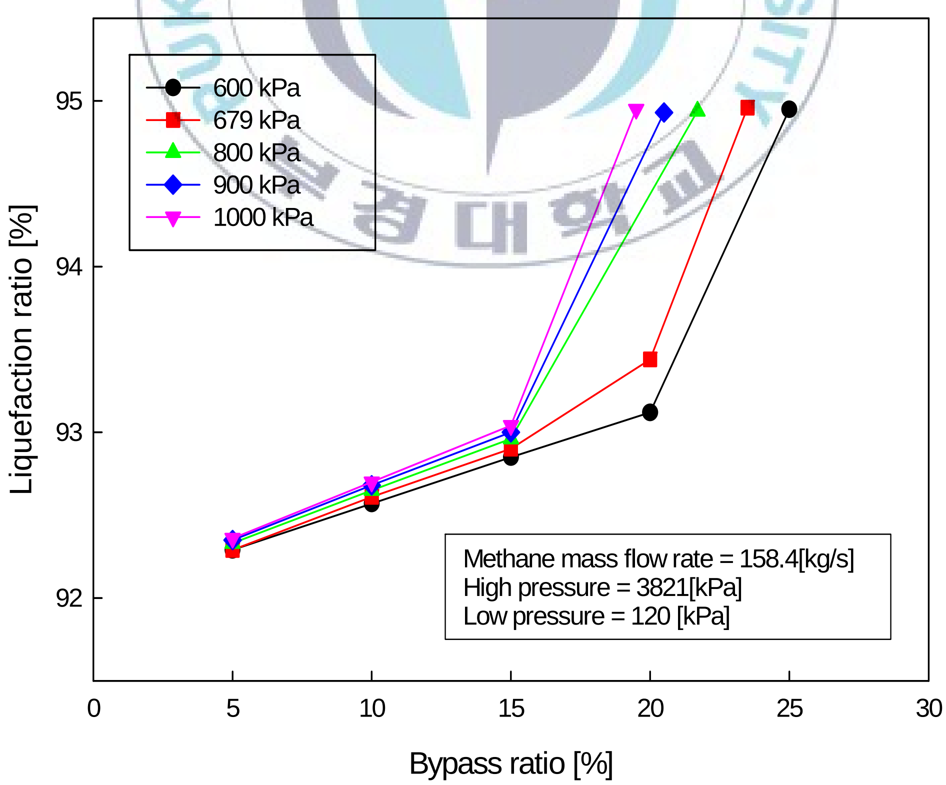
a) Comparison of compressor work as a bypass ratio



b) Comparison of refrigeration capacity work as a bypass ratio



c) Comparison of COP as a bypass ratio



d) Comparison of Liquefaction ratio as a bypass ratio

4.6 Performances of modified Methane cycle

1.4. Comparison of Performances with Basic Process

In this section, performances of cascade process using two staged compression type with inter-cooler are compared with basic cascade process in 92% of liquefaction ratio and 160.1℃ of liquefaction temperature. Results are shown in Fig. 4.7, and basic cascade process, propane cycle using inter-cooler, propane and ethylene cycles using inter-cooler and whole cycles using inter-cooler are named Basic, Modified C3, Modified C3+C2 and Modified all in this section. Compressor work of Modified all is shown lowest value with 338.68 MW and it is lower 16.34% than that of basic process as shown in Fig. 4.7.a. According to applying inter-cooler, supercooling is increased and therefore refrigeration effect is increased. In other words, refrigeration capacity is calculated by multiplying refrigeration mass flow rate and refrigeration effect, so increment of refrigeration effect means refrigerant mass flow rate was decreased in a same refrigeration capacity. For this reason, it can be decided that decrement of refrigerant mass flow rate has a effect on the compressor work. Also, evaporated refrigerant which has low temperature in the inter-cooler is mixed with exhausted gaseous refrigerant which has high temperature from the low stage compressor, then temperature of refrigerant which flows into high stage compressor drops down. This is one of the factor which effects decrement of compressor work.

Fig. 4.7.b shows comparison of refrigeration capacity. refrigeration capacity shows decreasing tendency as applied inter-cooler and that of Modified all is shown lowest value with 449 MW. According to increment of supercooling, refrigeration capacity is increased basically, but this means that refrigeration capacity is increased in a same refrigerant mass flow rate. However, refrigerant mass flow rate should be decreased to target of liquefaction ratio with 92% to compare with basic cycle. For this reason, it can be decided that refrigeration capacity is decreased because of decrement of refrigerant flow rate.

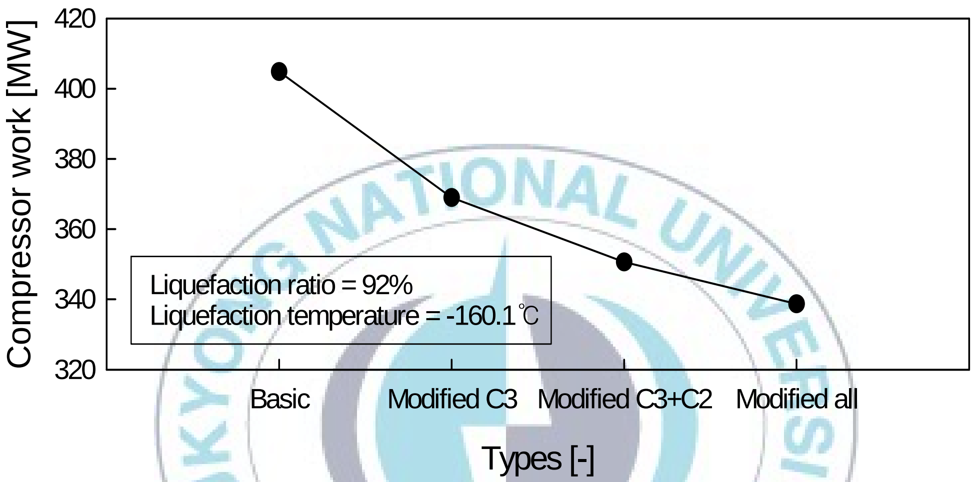
COP is shown in Fig. 4.7.c. It is increased as applied inter-cooler, and Modified all is shown highest value with 1.33. It is shown that COP is increased because decrement of compressor work by applied inter-cooler is higher than that of refrigeration capacity.

Next, specific power (Power consumption per LNG productivity) and LNG productivity (LNG productivity per power consumption) which are the most important parameter in the performance evaluation of liquefaction process are shown in Fig. 4.7.d and 4.7.e. Specific power is decreased and productivity is increased as applied inter-cooler. decrement of specific power and increment of productivity mean to improve liquefaction ability of process because same production LNG can be produced with lesser compressor work. Specific power of Modified all is shown lowest value with 2135.44 kJ/kg and it is lower 16.29% than Basic, and productivity of that is shown highest value with 1.74

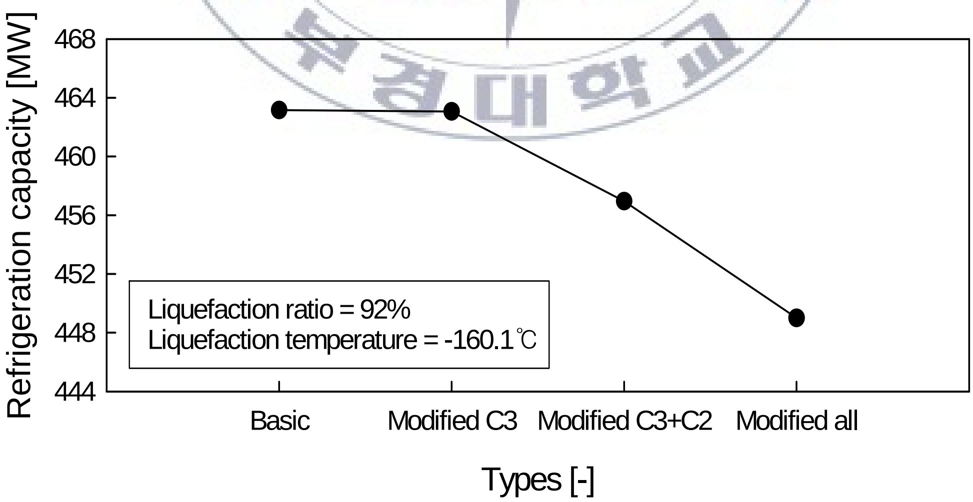
kg/h/kW and it is higher 19.46% than Basic.

Refrigerant mass flow rate is compared in Fig. 4.8. Propane, ethylene and methane of Modified all are decreased about 8.84%, 4.58% and 2.15% respectively. It can be known that refrigeration mass flow rate has a great effect on compressor work and refrigeration capacity. Especially, propane mass flow rate is decreased largely, this is because propane cycle plays a primary role such as pre-cooler to methane cycle and condenser to ethylene cycle.

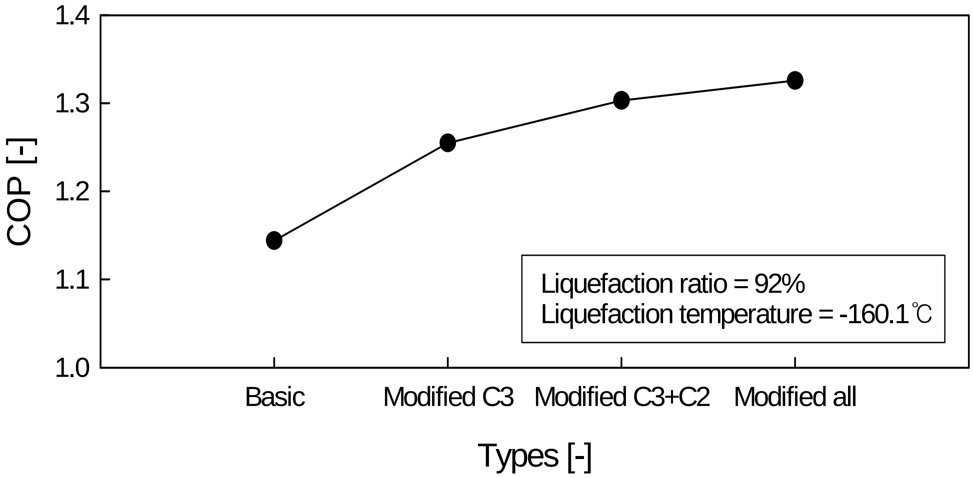
These results are used to condition for standard cascade process using two staged compression type with inter-cooler.



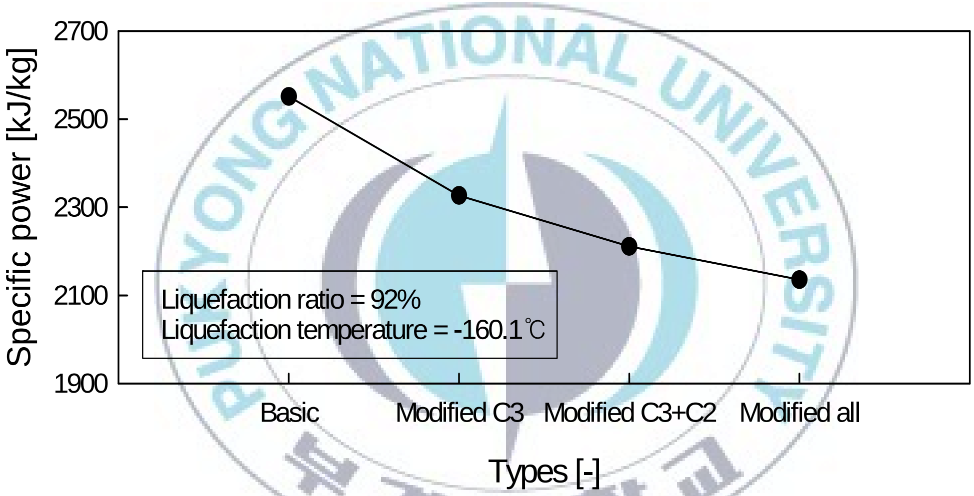
a) Comparison of compressor work as a types



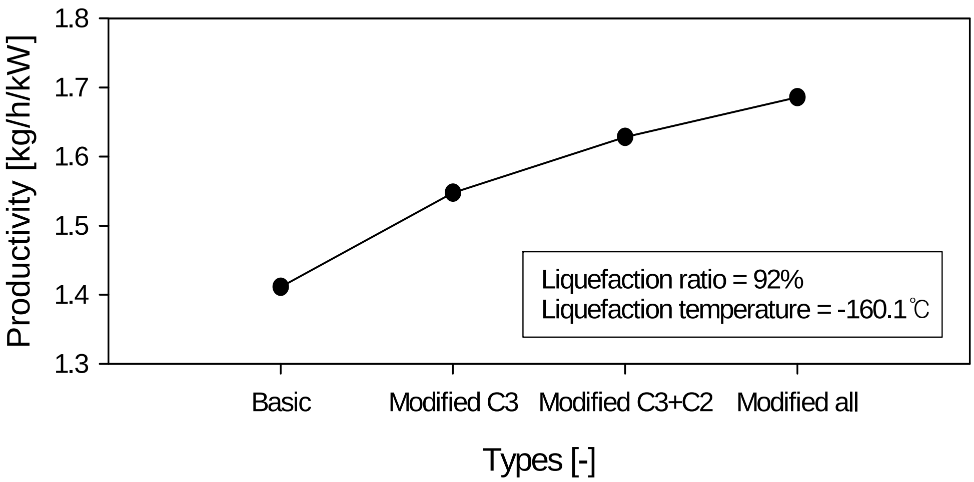
b) Comparison of refrigeration capacity as a types



c) Comparison of COP as a types

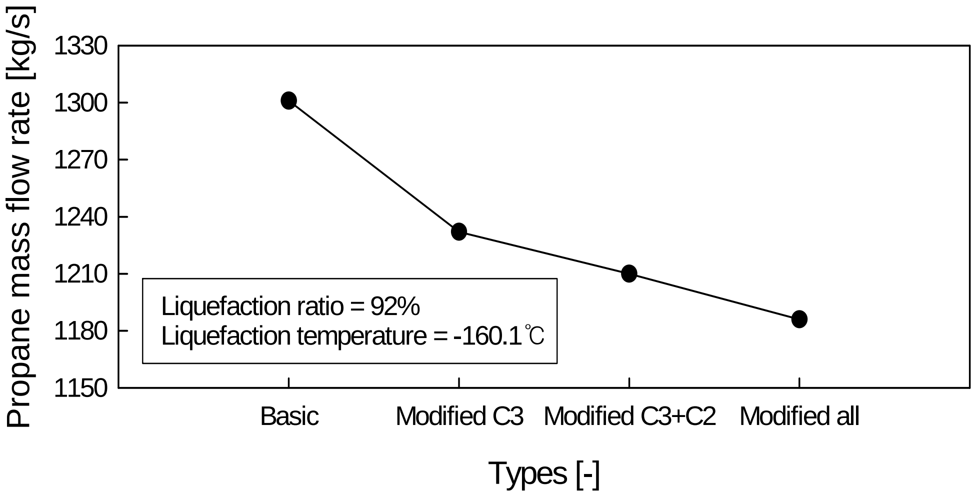


d) Comparison of specific power as a types

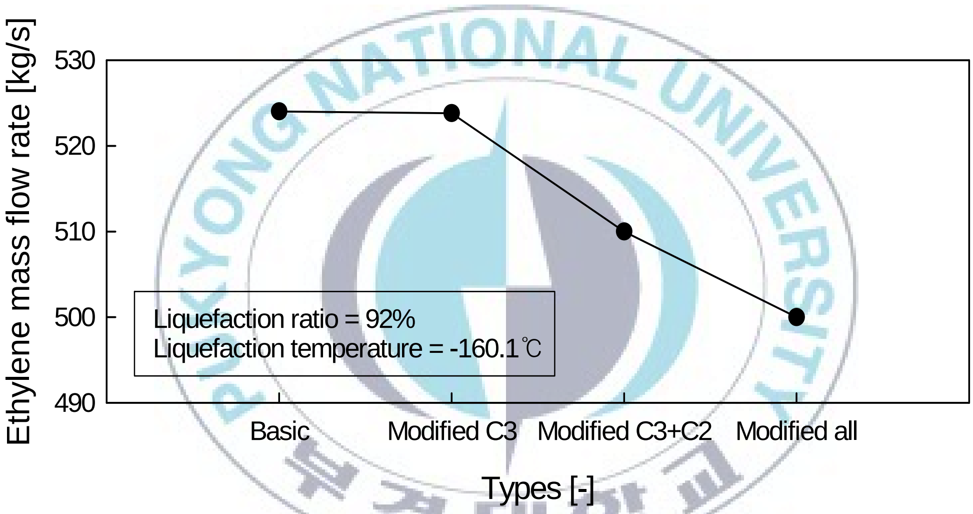


e) Comparison of specific power as a types

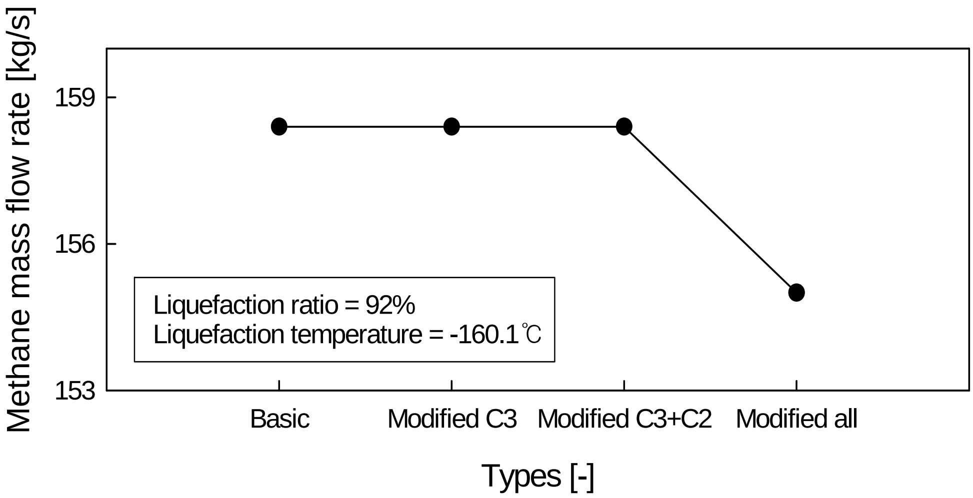
4.7 Comparison of performances



a) propane mass flow rate



b) Ethylene mass flow rate



c) Methane mass flow rate

4.8 Comparison of refrigerants mass flow rate

2. Two Staged Inter-cooler Cascade using Expander

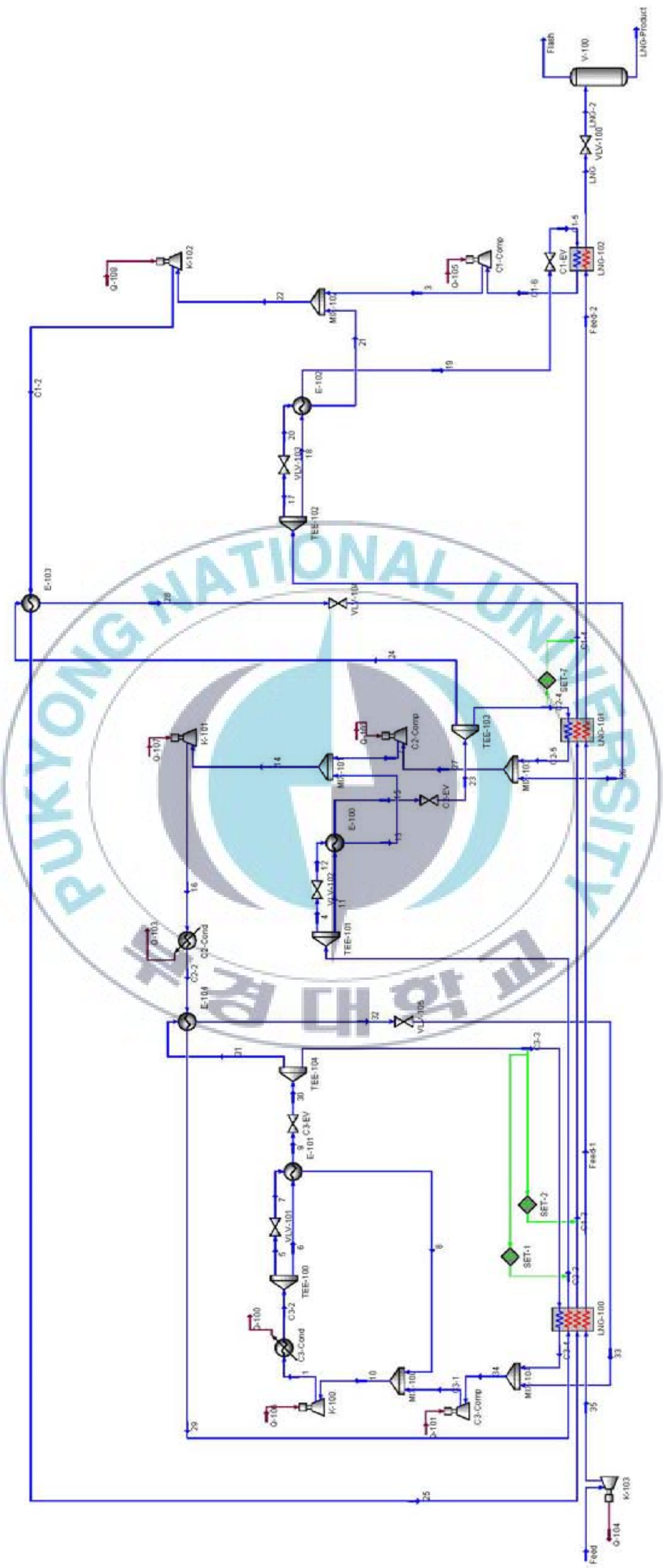
In this section, Expander is applied to above process which includes two liquid-gas heat exchanger. Just extracted natural gas form the gas field at a high pressure with 5000 kPa, but poduced LNG from liquefaction process is stored at a low pressure with 103.3 kPa as atmosphere. Therefore, expander is applied in front of propane evaporator to improve efficiency of process with reducing pressure drop in a liquefaction processing. Process diagram of practical simulation is shown in Fig. 4.9. Results are shown in Fig. 4.10, and above process and applied expander to above process are named Inter-cooler and each pressure drop.

Compressor work of 600 kPa is shown lowest value with 327.76 MW and it is lower 0.33% than Inter-cooler. However, compressor work is increased from up to 600kPa. Natural gas is cooled to set temperature which is related to pressure drop as it is expanded in the expander. After this, cooled natural gas flows into evaporator of propane, and it reduces load of process, so liquefaction efficiency and liquefaction ratio are improved. Because of this, refrigerant mass flow rate can be reduced by reducing improved liquefaction ratio to 92%. As a result, compressor work is decreased and also, the power which is produced from expander as 1.842 MW can be reduced.

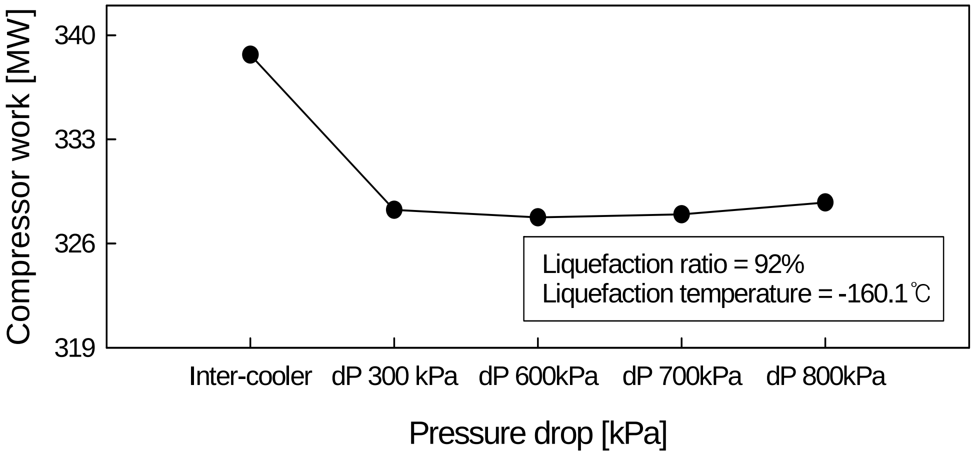
Fig. 4.10.b and Fig. 4.10.c shows refrigeration capacity and COP. Refrigeration capacity also is decreased, but it is increased from up to 600 kPa. It is decreased by 0.21%, 0.44%, 0.39% and 0.18% respectively as 300 kPa, 600 kPa, 700 kPa, 800 kPa. COP is shown constant value with 1.32 because decrement ratio of compressor work is larger than that of refrigeration capacity.

Next, specific power and productivity are shown in Fig. 4.10.d and Fig. 4.10.e. Specific power shows lowest value with 2066.58 kJ/kg, and it is lower 0.27% than Inter-cooler at 600 kPa. LNG productivity shows constant value with 1.74. In this simulation, it can be decided that performance of 600 kPa is the best because specific power shows lowest value.

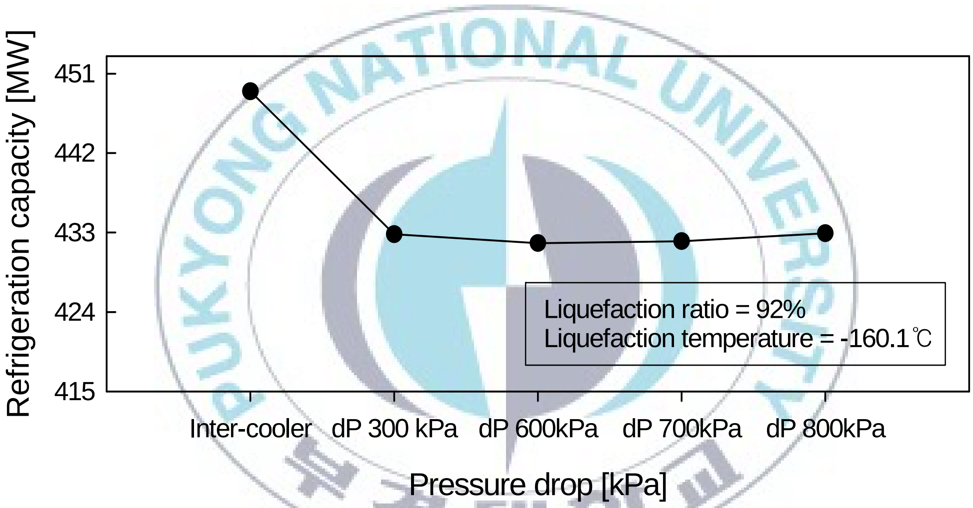
Fig. 4.11 shows comparison of refrigerant mass flow rate. It gives cooling effect to process by expanding feed gas. As a result, refrigerant mass flow is reduced by same reason of compressor work decrement. Mass flow rate of propane is decreased, but it is increased from up to 700 kPa. Also, mass flow rate of ethylene is decreased, but it is increased from up to 600 kPa. However mass flow rate of methane shows constant tendency.



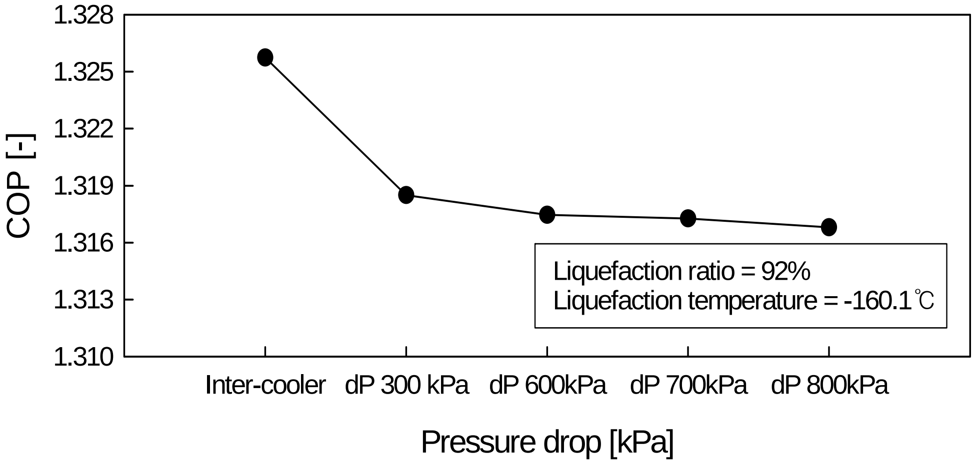
4.9 Simulation design of 2 staged inter-cooler cascade using Expander



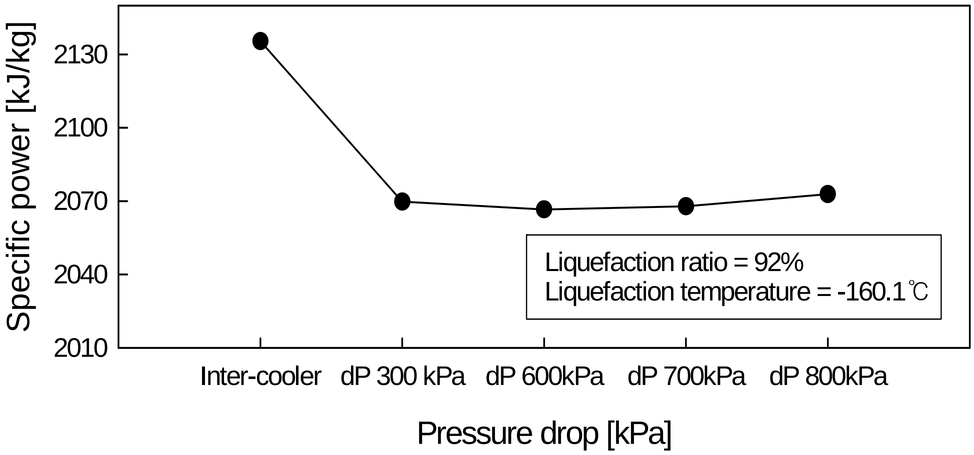
a) Comparison of compressor work as a pressure drop



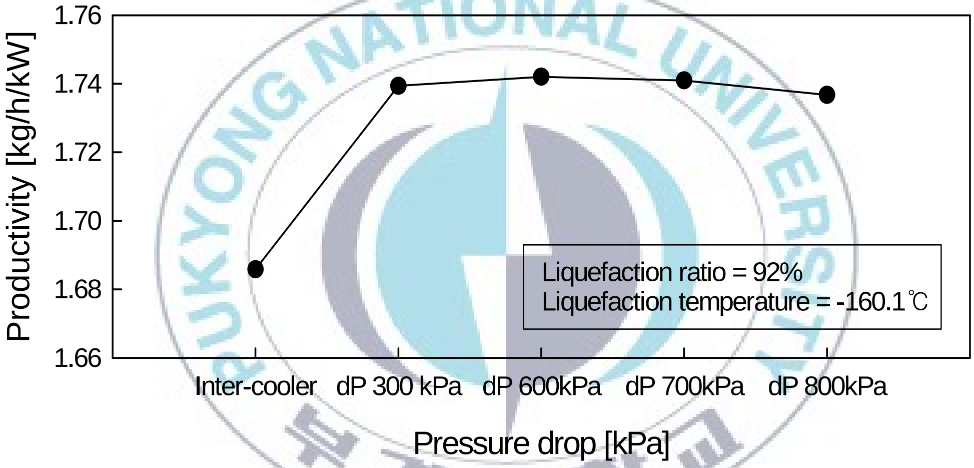
b) Comparison of refrigeration capacity as a pressure drop



c) Comparison of COP as a pressure drop

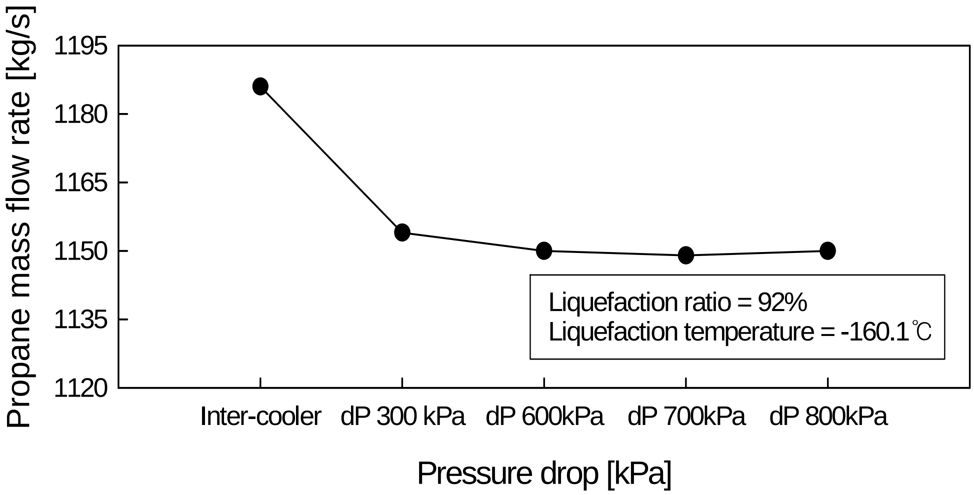


d) Comparison of specific power as a pressure drop

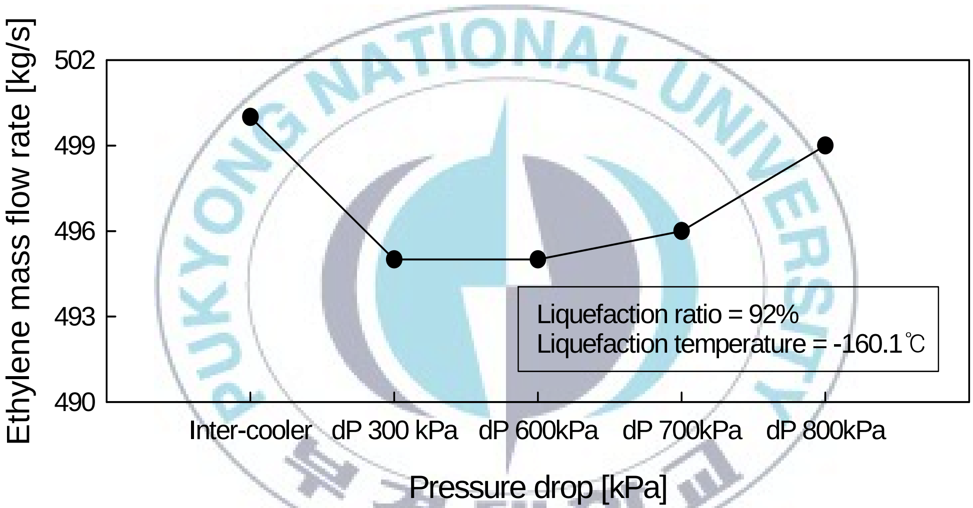


e) Comparison of specific power as a pressure drop

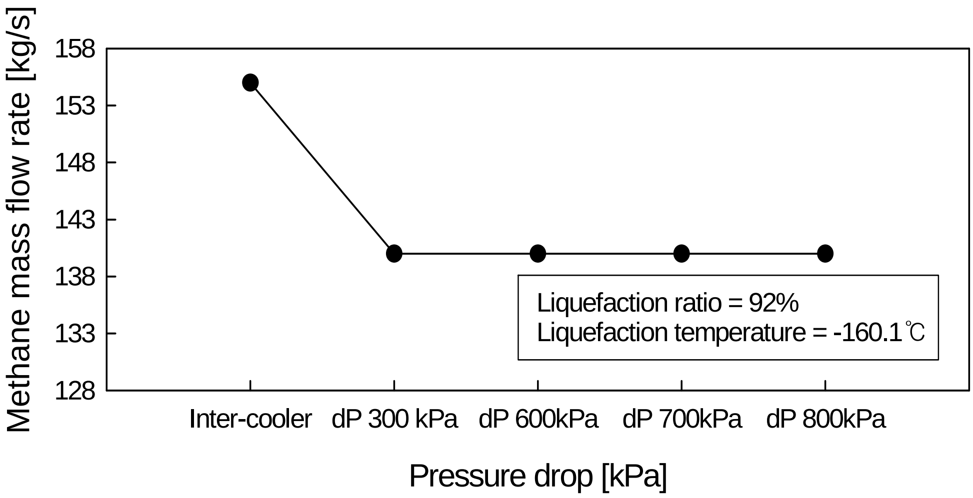
4.10 Comparison of performances



a) propane mass flow rate



b) Ethylene mass flow rate



c) Methane mass flow rate

4.11 Comparison of refrigerants mass flow rate

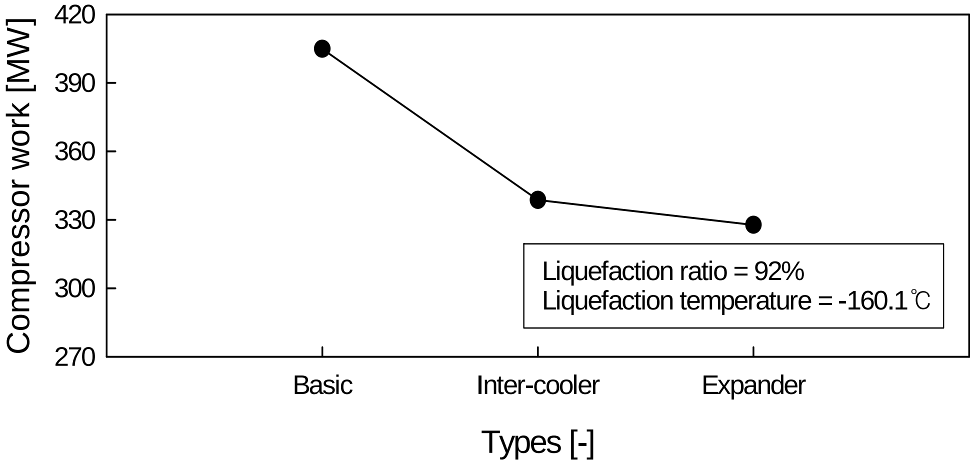
3. Comparison of Performances as Each Process

In this section, results of whole simulated process is compared in Fig. 4.18 and 4.19. Basic cascade process, two staged cascade process with inter-cooler and applied liquid-gas heat exchanger and expander to above process are named Basic, Inter-cooler and Expander. Compressor work and refrigeration capacity shows decreasing tendency as being modified. According to applied inter-cooler, liquid-gas heat exchanger and expander, liquefaction efficiency and liquefaction ratio are improved. Because of this, refrigerant mass flow rate can be reduced by reducing improved liquefaction ratio to 92%. Compressor work of Expander is shows lowest value with 327.76 MW, and it is lower 19.04% than Basic. In refrigeration capacity also, it shows lowest value 431.81 MW, and it is lower 6.77% than Basic. COP of Inter-cooler is increased to 1.33, it is higher 15.88% than Basic. However, it is decreased to 1.32, and it is lower 0.52% than Inter-cooler as applied expander. This is because compressor work is decreased gradually, but refrigeration capacity is decreased constantly from Inter-cooler to Expander as shown in Fig. 4.18.a and Fig.4.18.b.

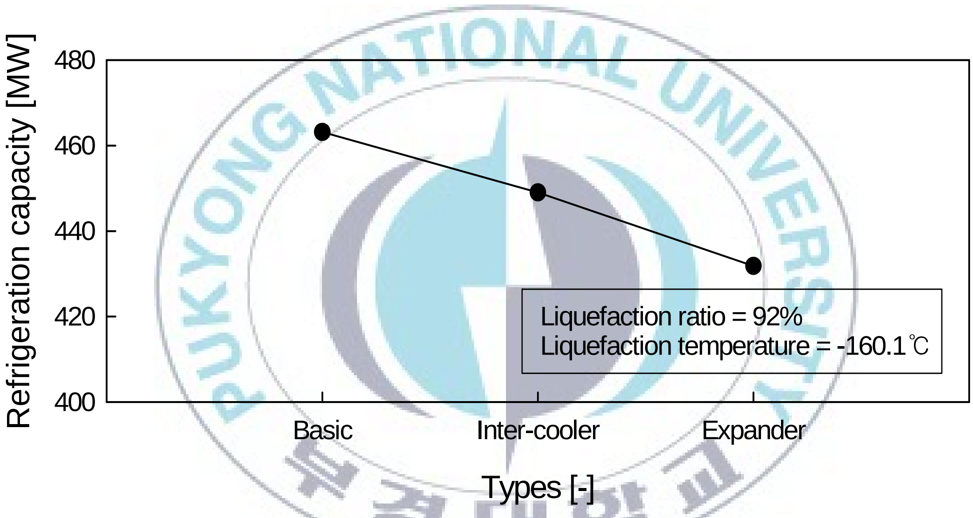
Fig. 4.18.d and Fig. 4.18.e shows specific power and LNG productivity. Specific power of Expander shows lowest value with 2066 kJ/kg, and it is lower 18.99% than Basic. Also, LNG productivity shows highest value with 1.74 kg/h/kW, and it is higher 23.44% than Basic.

Next, variation of refrigerant mass flow rate is shown in Fig. 4.19. It shows the decreasing tendency of all refrigerant mass flow rate as process is being modified. propane, ethylene and methane mass flow rate of Expander is fewer 11.6%, 5.53% and 11.62% than those of Basic. Like these decrement of refrigerant mass flow rate is the important parameter which can improve ability of liquefaction process.

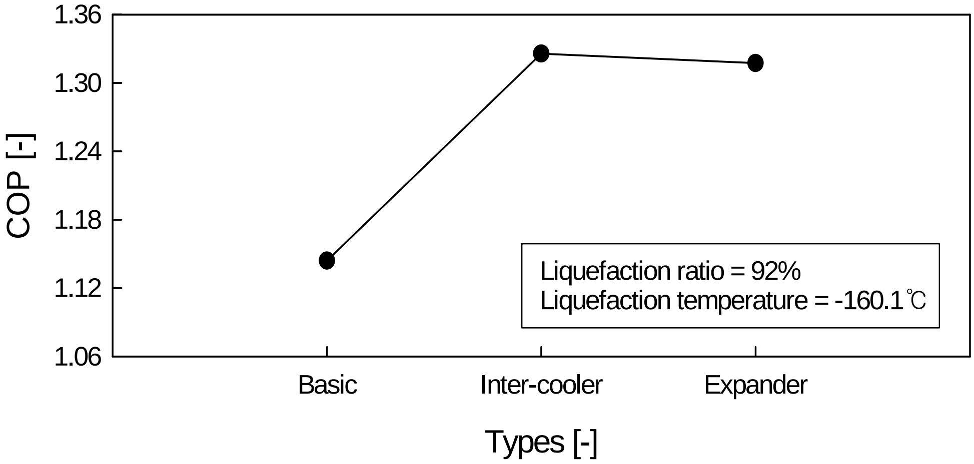
In these simulation, Expander shows best performance according to above reasons.



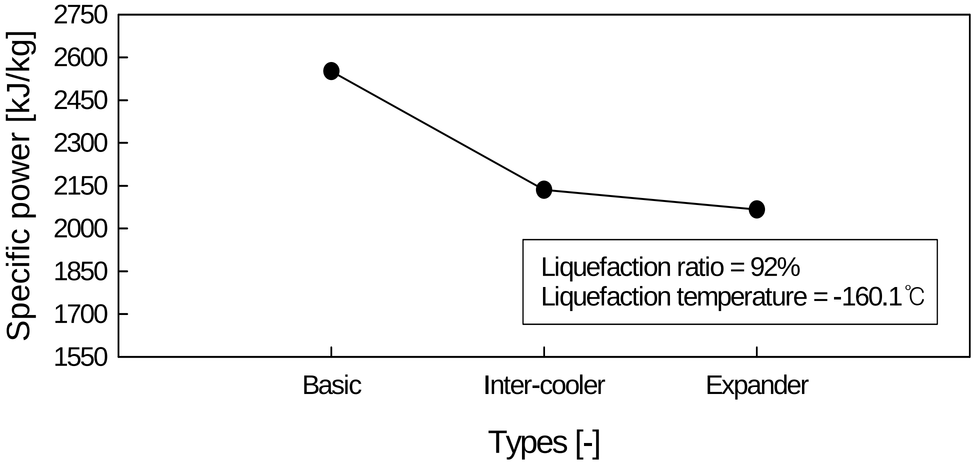
a) Comparison of compressor work as a type



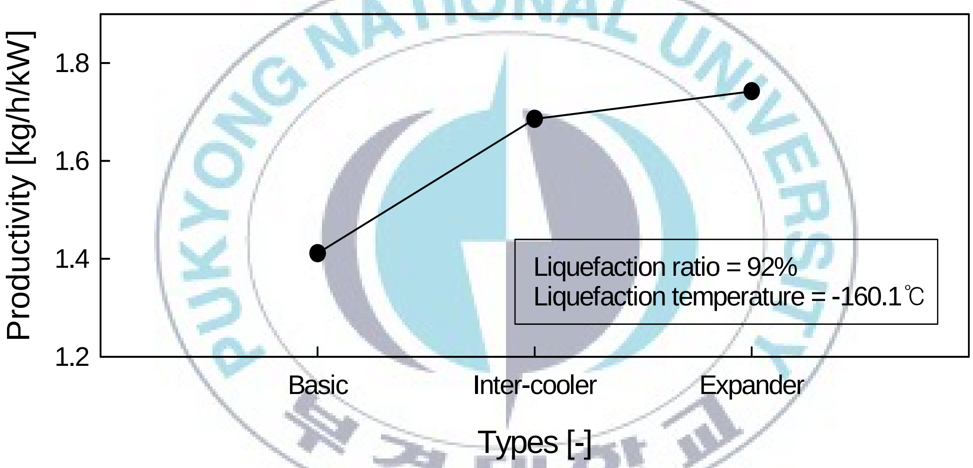
b) Comparison of refrigeration capacity as a type



c) Comparison of COP as a type

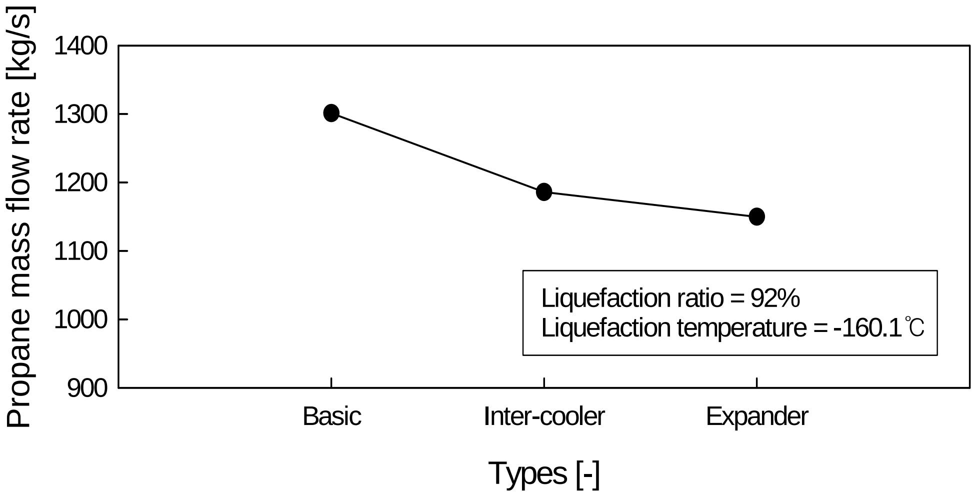


a) Comparison of specific power as a type

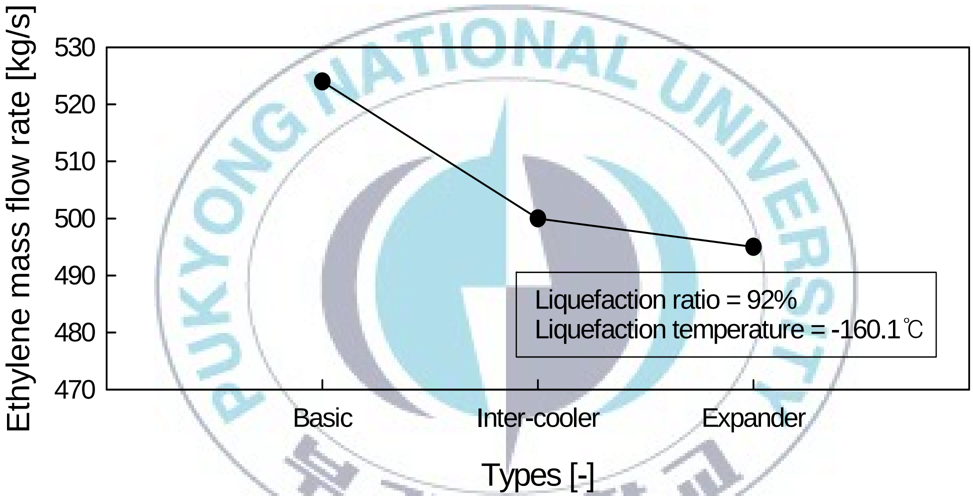


e) Comparison of productivity as a type

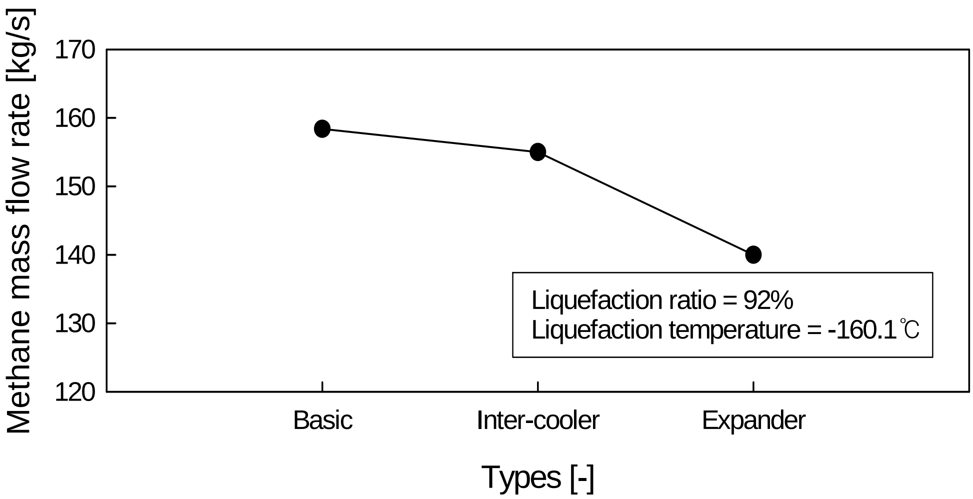
4.18 Comparison of performances



a) Propane mass flow rate



b) Ethylene mass flow rate



c) Methane mass flow rate

4.19 Comparison of refrigerants mass flow rate

V. Conclusion

In this research, performance characteristics of process which applied inter-cooler, liquid-gas heat exchanger and expander is figured out, and following conclusions are acquired.

1) Two staged compression type with inter-coolers is applied to propane, ethylene and methane cycles. Compressor work and refrigeration capacity of Modified all is decreased 16.34% and 15.88% respectively, and COP of that is increased 15.88% than Basic. Also, Modified all shows highest performance with decrement of specific power 16.29% and increment of LNG productivity 19.46%.

2) Compressor work and refrigeration capacity of Expander is decreased 19.04% and 6.77%, and COP of that is increased 15.88% than Basic. Specific power of Expander is decreased 18.99% and LNG productivity of that is increased 23.44% than Basic.

In this study, Expander which is two staged compression cascade using inter-cooler shows highest performances, these results are used to research to develop performance and efficiency of liquefaction process.

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그리고 수업과 세미나를 통해서 많은 가르침을 주신 오후규 교수님, 금종수 교수님, 김종수 교수님, 최광환 교수님, 정석권 교수님, 김은필 교수님 정말 진심으로 감사드립니다.

못난 아들 믿어 주시고 항상 용기를 주시는 아버지, 어머니..그동안 고생 많으셨고..수고하셨습니다. 부모님 사랑합니다. 그리고 동생을 항상 자랑스럽게 여겨 준 누나..고맙고, 내가 누나 사랑하는 거 알지? 그리고 논문 영작에 도움을 준 기성이 형, 항상 응원해 줬던 재훈이 형, 재민이 형, 이쁜 동생 세은이, 석찬이, 석원이, 친척들 모두 감사하고 사랑해요.

좋은 말씀과 조언을 해주셨던 춘근이 형과 동훈이 형 선배님, ENSYS실험실 선배님들 감사합니다. 항상 저에게 따끔한 충고와 따뜻한 조언을 해주신 창효 형 감사합니다. 저에게 열심히 하라던 말씀, 항상 가슴속에 기억하고 있습니다. 그리고 저에게 많은 관심을 가져줬던 승문이형, 항상 어머니 같이 챙겨주셔서 감사합니다. 그리고 에너지 시스템 연구실에 들어와서 실험이 뭔지..논문이 뭔지 몰랐던 저에게 많은 것을 알려주고 깨달게 만들어 주신 호생이 형.. 덕분에 지금의 제가 만들어 진것 같습니다. 배울 당시에는 힘들고 괴로웠지만.. 그게 다 저를 위한 채찍질이었단 것을 알게 된 지금은 형에게 감사할 다름입니다. 졸업했지만 아직까지 저를 괴롭혀 주시는 규진이 형.. 항상 나의 불만을 들어주고 아낌없이 조언 해주던 형덕에 이렇게 무사히 졸업 할 수 있는 것 같네요. 제발 미국 쫌 가세요. 그리고 1년동안 창원 LG에서 고생했던 병주형.. 형덕에 실험에 대해서 더 알게 되고 형 뒤를 이어 용접에 달인이 될 수 있었던 것 같아요. 감사합니다.

그리고 내 밑에서 욕먹느라 고생한 동생들..현우..원재..진우..1년 넘도록 내 비위 맞추느라 고생 많았고 항상 열심히 하는 모습 보기 좋다. 힘들고 괴로워도 항상 웃음 잃지 말고..수고했고..고맙다. 그리고 우리 실험실 막네 슈퍼 루저 현승이..니덕에 형이 웃으면서 생활했다. 이번에 미국 가서 많은 것 보고 배워서 더 큰 현승이가 되서 돌아와라. 1년 동안 수고 많았다. 이번에 새로 들어온 현수..아직은 생소 하겠지만 더 열심히 배우고 노력해서 멋진 현수가 되거라. 우리 연구실 동생들 형 뒤치다꺼리 하느라 고생했다. 저 때문에 고생하신 산학협력단에 인원쌤 감사하구요.. 앞으로도 잘부탁 드려요.. 그리고 가스공사 관계자 분들께도 감사의 말씀드립니다.

많이 모지란 저에게 일본어를 주입 시키시느라 고생하시는 창희 형, 엄마 같은 부경쌤, 아빠 같은 주형쌤 항상 감사하고 있어요. 앞으로도 잘 부탁드려요.

모든 분들의 도움으로 이 논문을 마무리 하게 되었습니다. 감사드립니다.