[UCI]I804:21031-200000225004

Thesis for the Degree of Master of Engineering

Experimental Study on the Performance Characteristics of Cascade Refrigeration System with R-404A/R-23

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August 2019

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(R-404A/R-23 냉매를 적용한 캐스케이드 냉동시스템의 성능특성에 관한 실험적 연구)

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by

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A thesis submitted in partial fulfillment of the requirements
for the degree of
Master of Engineering

in the Department of Refrigeration and Air Conditioning Engineering
The Graduate School
Pukyong National University

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August 23, 2019

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Experimental Study on the Performance Characteristics of Cascade Refrigeration System with R-404A/R-23

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Abstract

저온 냉동은 식품 저장, 의료기기, 반도체 공정 등 다양한 분야에서 사용되고 있다. 일반적으로 저온 냉동 방법에는 대표적으로 다단 압축 냉동시스템, 혼합냉매를 이용한 오토 캐스케이드 냉동시스템 등이 있다. 캐스케이드 냉동시스템의 경우 고온부(HTC, High temperature circuit)와 저온부(LTC, Low temperature circuit)로 독립된 2대의 독립된 냉동기로 이루어져 있기 때문에 장치가 차지하는 면적은 크지만 안정적으로 저온영역에 도달할 수 있다는 장점이 있고, 사용 온도 범위가 영하에서 높게는 영상 온도까지 사용할 수 있기 때문에 경제성 면에서 이득이 있어 산업현장에서 주로 사용되는 시스템이다. 캐스케이드 시스템에서 고온부는 주로 비등점이 높은 냉매를 사용하며, 저온부는 저온영역까지 도달할 수 있는 비등점이 낮은 냉매를 사용한다. 캐스케이드 냉동시스템의 장점 중 하나는 바로 비등점이 낮은 냉매의 응축 과정이다. 캐스케이드 냉동시스템은 고온부의 증발기와 저온부의 응축기 역할을 하는 캐스케이드 열교환기를 통해 상당히 낮은 온도에서 응축이 가능하다. 하지만 캐스케이드 열교환기 내에서의 열 유동은 고온부와 저온부 각각 개별적으로 이루어지는 것이 아니라 동시에 이루어지기 때문에 캐스케이드 열교환기에서

고온부의 증발온도 혹은 저온부의 응축온도를 어떻게 설계하느냐에 따라 캐스케이드 냉동시스템의 성능이 결정된다. 하지만 대부분 시뮬레이션 분석을 통한 시스템 성능예측의 논문 [1-16] 이고 실제 장치를 설계하여 가동 시 여러 작동 변수에 대한 (ex. 압축기의 체적효율 및 압축효율 등)은 고려를 하지 않았기 때문에 최적의 운전조건을 모색하는 데에는 한계가 있어 보인다. 따라서 본 연구에서는 R-404A/R-23 냉매를 이용하여 여러 가지 조건에서 캐스케이드 냉동시스템의 성능 특성을 실험적으로 분석하였고, 이에 대해 R-404A/R-23 냉매군에 대한 최적의 운전조건에 대한 결과를 제시하였다. 결과를 요약하면 다음과 같다. 고온부의 응축온도가 증가함에 따라 고온부 사이클의 성능계수는 낮아지고, 저온부 사이클의 성능계수는 거의 일정하게 유지되는 경향을 보였다. 이에 따라 총괄 COP는 감소하는 경향을 보였으며, 이는 고온부 사이클에 영향을 크게 받은 것으로 여겨진다. 저온부의 응축온도가 증가함에 따라 고온부 사이클의 성능계수는 큰 변화는 없었으나, 저온부 사이클의 성능계수는 상승하는 경향을 보였다. 이에 따라 총괄 COP는 증가하는 경향을 보였으며, 이는 저온부 사이클의 영향을 크게 받은 것을 알 수 있었다. 저온부의 응축온도가 증가함에 따라 고온부 사이클의 성능계수는 낮아지고, 저온부 사이클의 성능계수는 높아지는 경향을 보였다. 이에 따라 총괄 COP는 일정 저온부 응축온도까지 상승하다 감소하는 경향을 보였다. 이는 곧 최적의 총괄 COP를 갖는 저온부 응축온도가 존재한다는 점이고, 실험적 변수인 고온부 증발온도, 저온부 증발온도의 실험 결과와 종합하여 사용 목적 온도에 따른 캐스케이드 냉동시스템의 최적 저온부 캐스케이드 열교환기의 응축온도에 대해 제시하였다.

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NOMENCLATURE

SYMBOLS

HTC	High temperature circuit	[-]
LTC	Low temperature circuit	[-]
P	Pressure	[MPa]
T	Temperature	[kW]
Q	Heat capacity	[kW]
V	Volumetric flow rate	[L/min]
c	Specific heat	[J/kg·K]
m	Mass flow rate	[kg/h]
h	Enthalpy	[kJ/kg]
W	Compressor work	[kW]
COP	Coefficient of performance	[-]

GREEK SYMBOLS

Δ	Difference	[-]
ρ	Density	[kg/m^3]

SUBSCRIPTS

opt	Optimum	[-]
H	High temperature circuit	[-]
L	Low temperature circuit	[-]
evap	Evaporator	[-]
cond	Condenser	[-]
b	Brine	[-]
comp	Compressor	[-]
cas	Cascade heat exchanger	[-]
in	Inlet	[-]
out	Outlet	[-]
O	Overall	[-]

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Low-temperature freezing is used in various fields such as food storage, medical equipment, and semiconductor processing. Generally, low-temperature refrigeration systems include multi-stage compression refrigeration systems and auto-cascade refrigeration systems using mixed refrigerants. In the case of multi-stage compression refrigeration systems, R-134a and R-502 are mainly used as refrigerants. But there is a limit to obtaining low-temperature. That is, to operate at a low evaporation temperature of about -70°C, the compression ratio becomes large, which causes a decrease in the compression efficiency and the coefficient of performance.

Also, the specific volume of the vapor is considerably large, and if the suction pressure drops below 0.1 bar, the compressor will be damaged. And the refrigerants with a low boiling point, such as R-23 and R-508B, the condensation pressure is too high to condense with water or air, resulting in a device strain. In the case of an auto-cascade refrigeration system using a mixed refrigerant, since a single-stage compression refrigeration system is used, the structure is simple and compact. However, it operates with one compressor to reach low-temperature, the efficiency is considerably lowered. Also, because auto-cascade refrigeration system uses zeotropic refrigerant, if it is influenced by leakage, the mixing composition ratio changes, and the cooling capacity does not come out properly.

In the case of the cascade refrigeration system, because it is composed of two independent refrigeration systems, the unit occupies a large area, but it has the advantage of reaching stable to low-temperature region. Also, it can be economically used because the operating temperature range is from minus to plus. Therefore, cascade refrigeration systems are widely used in the industrial field.

The basic schematic of the cascade refrigeration system is shown in Fig. 1.1 and the P-h diagram is shown in Fig. 1.2. As shown in Figure 1.1, the system is two independent systems with a high-temperature circuit (HTC) and a low-temperature circuit (LTC). The HTC mainly uses a refrigerant having a high boiling point and the LTC uses a refrigerant having a low boiling point which can reach a low-temperature area. One of the advantages of the cascade refrigeration system is the condensation process of the low boiling point refrigerant. In the case of the multi-stage compression refrigeration system or the auto-cascade refrigeration system, the condensation is performed at room temperature, but the cascade refrigeration system is capable of condensing at a low temperature through the evaporator of the HTC, called cascade heat exchanger. However, since the heat flow in the cascade heat exchanger is not performed individually but at the same time, the performance of the cascade refrigeration system depends on how the evaporation temperature of the HTC or the condensation temperature of the LTC is designed in the cascade heat exchanger.

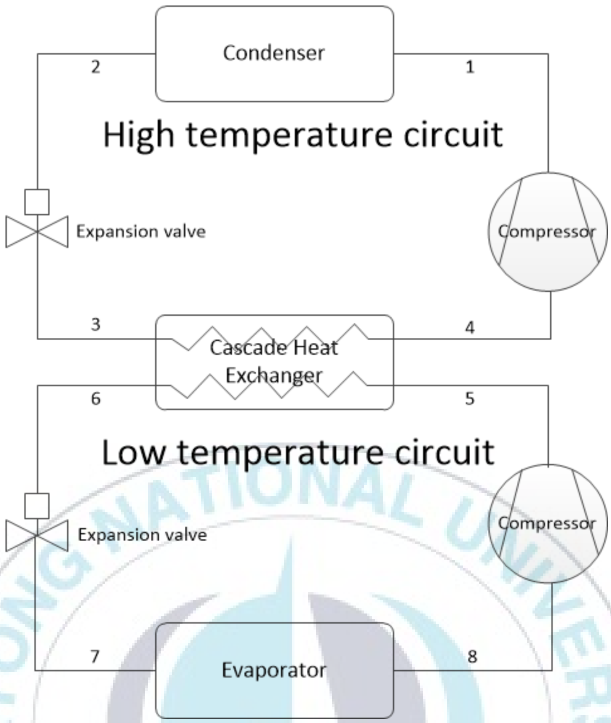

Fig. 1.1 Schematic diagram of cascade refrigeration system

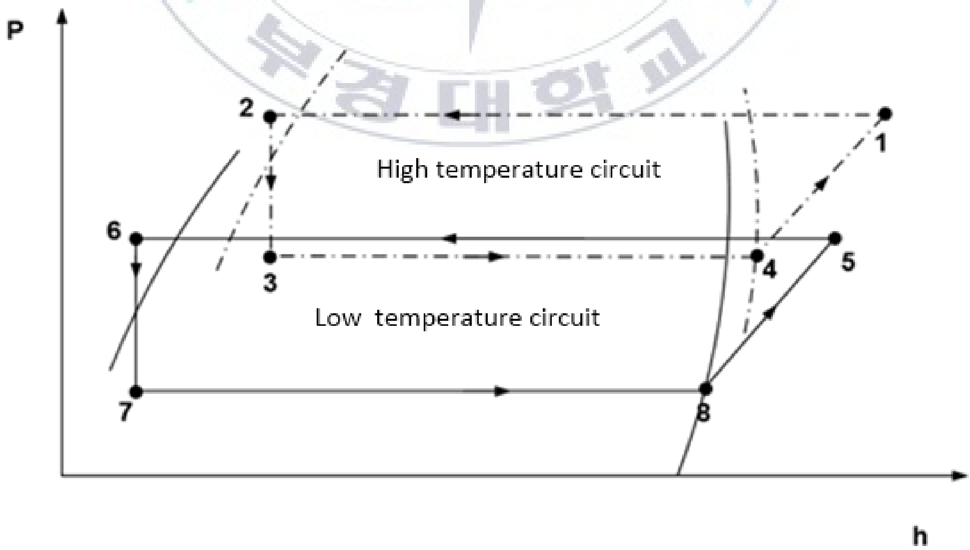

Fig. 1.2 Pressure-enthalpy diagram of cascade refrigeration system

1.2 REVIEW OF PREVIOUS WORKS

A study on the representative cascade refrigeration system that has been published so far in relation to this paper is as follows.

First, Kilicarslan et al. [1] analyzed the energy and irreversibility of the cascade refrigeration system using the developed computer code and R-152a/R-23, R-290/R-23, R-507/R23, R-234a/R23 and R-404a/R23 were used. The analyze conditions were as follow. The cooling capacity is 1 kW, the cooling temperature is -40°C, and the ambient temperature is 27°C. The subcooling degree of the condenser and the superheating degree of the evaporator are 5°C and 7°C, respectively. They also assumed that the polytropic efficiency of the compressor is the same. The results show that the COP of the cascade refrigeration system increases and the irreversibility decreases with increasing evaporator temperature and polytropic efficiency for all refrigerant groups. On the other hand, the COP of a cascade refrigeration system decreases and irreversibility increases when the saturation temperature difference (ΔT) in the LTC and the HTC in the heat exchanger and the condenser temperature are increased.

Prekh et al. [2] performed the thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R-13/R-12, R-290/R-23, and R-404A/R23. Effect of various operating parameters i.e. evaporator temperature, condenser temperature, temperature difference in cascade condenser and low temperature cycle condenser temperature on performance parameters viz. COP, exergetic efficiency and refrigerant mass flow ratio have been studied. Thermodynamic analysis shows that out of three refrigerant pairs R-12/R-13, R-290/R-23 and R-404A/R-23 the COP of R-290/R-23 refrigerant pair is highest.

Sun et al. [3] confirmed that R-41 is a suitable alternative refrigerant for R-23 through comparison of thermodynamic performance of R-404A/R-41 and R-404A/R-23 cascade refrigeration systems. The results show that the optimum condensation temperature exists for the LTC (T_{opt}) where the COP obtains the maximum value. The R-404A/R-41 refrigerant power consumption was lower than that of R-404A/R-23, and COP_{opt} was higher than that of R-404A/R-41. The maximum exergy efficiency of R-404A/R-41 and R-404A/R-23 was 44.38% and 42.98%, respectively. This theoretical analysis shows that the R-404A/R-41 is a more efficient combination of refrigerants than the R-404A/R-23.

Parekh et al. [4] studied with the thermodynamic analysis of cascade refrigeration systems using ozone-friendly refrigerants R-507A and R-23. R-507A is an azeotropic mixture consisting of HFC refrigerant with R-125/R-143a (50%/50% wt). This study was conducted to investigate the effects of the HTC condensation, and evaporation temperature, subcooling, and superheating degree, a temperature difference of cascade heat exchanger, LTC condensation, and evaporation temperature, subcooling, and superheating degree. Finally, there were variables with the highest COPs in R-507A/R-23 cascade refrigeration system.

Kasi [5] analyzed the cascade refrigeration system to select the best refrigerant group for the HTC and LTC in various alternative refrigerant groups (R-134a/R-23, R-290/R-23, R-404A/R-23, R-407C/R-23, R-410A/R-23, R-134a/R-508B, R-290/R-508B, R-404A/R-508B, R-407C/R-508B, R-410A/R-508B, R-134a/R-170, R-290/R-170, R-404A/R-170, R-407C/R-170, R-410A/R-170). The analysis conditions were assumed to be 5°C and 10°C for subcooling and superheating degree, respectively. The HTC condensation temperature was set to 30°C to 50°C and the LTC evaporation temperature was set to -70 to -50°C. The temperature in the cascade heat exchanger is assumed to be about 20°C, and the efficiency of the compressor is assumed to be 0.7. The results show that as the evaporation temperature increases for all refrigerant groups, the coefficient of performance of the cascade refrigeration system increases, and the mass flow rate on the HTC increases. On the other hand, the COP of the cascade refrigeration system decreases, the refrigerant mass flow rate at the HTC increases, and the power consumption of the compressor also increases as the condenser temperature increases. Finally, the refrigerant group R-134a/R-170 has the highest COP and the lowest mass flow rate, while the R-404A/R-508B has the lowest COP and the highest mass flow rate.

In a previous study, there was an optimum condensation temperature with the highest COP in a cascade heat exchanger. There are many papers on various refrigerant groups for cascade refrigeration systems [6-16], however, most of them are performed by prediction through simulation analysis, and various operating parameters (e.g. volumetric efficiency and compression efficiency of the compressor) are not considered. So there seems to be a limit to finding optimal operating conditions. Therefore, in this paper, the performance characteristics of a cascade refrigeration system according to the HTC evaporation temperature, LTC evaporation temperature, and LTC condensation temperature are experimentally analyzed using the R-404A /

R-23 refrigerant group, which is high in GWP, but still the most used in the overall industry.

1.3 PURPOSE AND SUMMARY OF THIS STUDY

Therefore, in this paper, the performance characteristics of the cascade refrigeration system using R-404A/R-23 refrigerant under various conditions are experimentally analyzed to clarify the cause and the actual desired In the design according to the temperature range, providing the fundamental data about the operating condition which shows the maximum coefficient of performance. Therefore, this paper is composed as follows.

In Chapter 1, the background of the study, content, and purpose was explained.

In Chapter 2, the experimental apparatus, experimental methods, conditions, and data reduction was explained.

In Chapter 3, the performance characteristics of the system were analyzed by measuring the pressure, temperature, flow rate, and power consumption of the system through experiments. Also, the results of this study are reviewed, and optimal operating conditions, including variables, are presented.

In Chapter 4, the results of this study were analyzed, and conclusions were drawn.

CHAPTER 2. EXPERIMENTAL APPARATUS AND METHOD

2.1 EXPERIMENTAL APPARATUS

Fig. 2.1 shows the schematic diagram of the cascade refrigeration system for the performance of the system with R-404A/R-23 refrigerant. Fig. 2.2 and 2.3 are actual experimental apparatus. And Table 2.1 ~ 2.3 are the specification of each components. As shown in Fig. 2.1, the system is divided into an HTC refrigerant line, LTC refrigerant line, and brine line. Initially, when HTC and LTC are entirely operated, the LTC condensation pressure rises excessively. So, at first, after running the HTC single compression refrigeration system, cool the brine sufficiently to lower the HTC evaporation temperature and then operates the LTC to decrease the condensation pressure.

First, the HTC refrigerant line, the high-temperature and high-pressure R-404A vapor discharged from the compressor passes through the oil separator, is condensed through the heat exchanger with the air in the condenser, and then passes through the receiver. Then, it passes through the HTC expansion valve after the filter drier, the sight glass, and the refrigerant mass flow meter. After passing through the HTC expansion valve, the refrigerant flows into the lower part of the evaporator, and after heat exchange with the brine, it goes to the upper part of the evaporator in the state of low-temperature and low-pressure gas and flows into the compressor through the gas-liquid separator. Then, when the Brine temperature decreases below a specific temperature, the HTC refrigerant passes through the mass flowmeter and the expansion valve, then goes to the cascade heat exchanger. After exchanges the heat with the LTC refrigerant and flows into the compressor through the gas-liquid separator.

In the LTC refrigerant line, the high-temperature and high-pressure R-23 refrigerant vapor discharged from the compressor is heat-exchanged with the R-404A liquid refrigerant in the cascade heat exchanger after the oil separator, condensed and passed through the internal heat exchanger. At this time, the refrigerant passes through the refrigerant mass flow meter after exchanges the heat with the low temperature and low-pressure gas refrigerant from the evaporator in the internal heat exchanger and flows into expansion valve. After that, the refrigerant flows into the upper portion of the LTC evaporator to facilitate oil recovery, and exchanges the heat with the brine, then flows out to the lower part of the evaporator, and the internal heat exchanger, exchanges the heat with the condensed R-23 liquid refrigerant. Then the superheated R-23 vapor refrigerant flows into the compressor.

The Brine line flows from the brine tank, the brine heater to the evaporator through the pump. The brine exchanges the heat with the refrigerant in the evaporator and flows back into the brine tank.

The compressor used in the experimental apparatus was a scroll type compressor and the condenser in the HTC was an air-cooled type pin-tube heat exchanger. HTC evaporator, the cascade heat exchanger and LTC evaporator were plate heat exchangers. For analyzing the performance characteristics of a cascade refrigeration system, a HTC condenser fan, HTC and LTC compressor, and brine pump used an inverter which can adjust the frequency of pieces of equipment. For control superheating degree, an electronic expansion valve was used. In particular, in LTC, if the refrigerant flows into the lower part of the evaporator, that may accumulate the oil at the bottom of the evaporator. So LTC refrigerant flows the evaporator upper side to lower side. Since the liquid refrigerant can flows into the compressor without being fully evaporated due to gravity, the remaining liquid refrigerant evaporated in the internal heat exchanger. Besides, the oil separator was installed on the discharge side of the compressor to facilitate oil recovery, and the stability of the system was increased by installing a receiver and a filter dryer at the outlet of the HTC condenser.

The temperature and pressure of the refrigerant were measured by attaching a pressure sensor and a temperature sensor in the inlet and outlet refrigerant tube of the main components for data analysis. The temperature sensor was attached to the tube to measure the temperature of the brine entering the HTC evaporator and the LTC evaporator, respectively. The flow rate of the refrigerant was measured by a mass flow meter, and the brine was measured by a volumetric flow meter. The compressor power consumption was measured using a power meter.

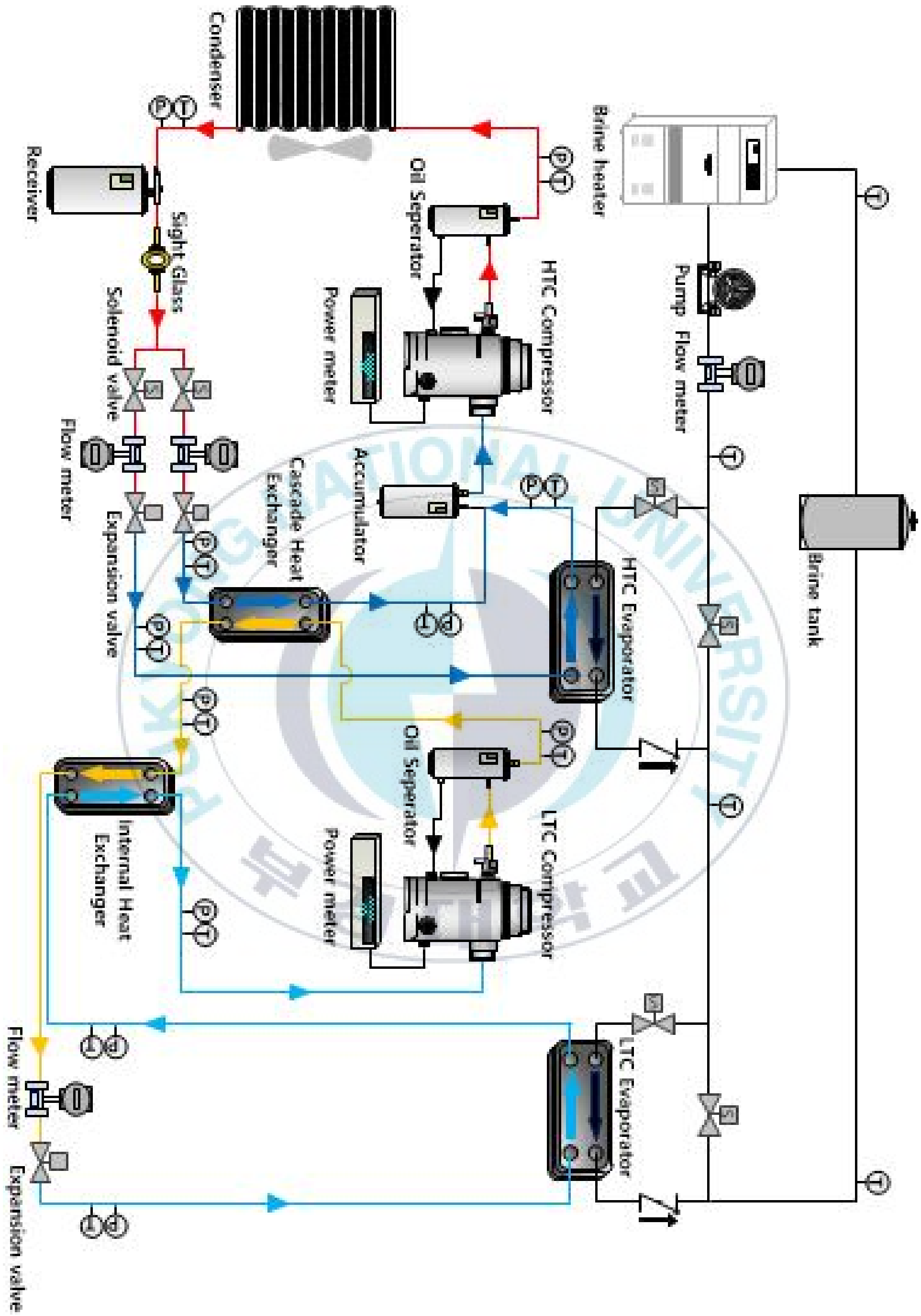

Fig. 2.1 Schematic diagram of experimental apparatus

Fig. 2.2 Experimental apparatus (Right side)

Fig. 2.3 Experimental apparatus (Left side)

Table 2.1 Specification of the main components used in this study

Compressor	HTC	Manufacturer : Emerson Model no. : ZF33K4E-TWD951 Type : Scoll Displacement : 34.74 m^3/h
	LTC	Manufacturer : Emerson Model no. : ZF18K4E-TF5 Type : Scoll Displacement : 20.59 m^3/h
Condenser	HTC	Manufacturer : Sejong Type : Air cooling
Electronic expansion valve	HTC LTC	Manufacturer : Emerson Model no. : EX5-U21 Step(pulse) : 0-750
Cascade heat exchanger		Manufacturer: Alfa laval Model no.: AC220EQ-36H Type: Counter flow brazed plate Capacity: 11 kW
Evaporator	HTC	Manufacturer: Alfa laval Model no.: AC220EQ-24M Type: Counter flow brazed plate Capacity: 5 kW
	LTC	Manufacturer: Alfa laval Model no.: AC220EQ-24M Type: Counter flow brazed plate Capacity: 5 kW

Table 2.2 Specification of the accessory components used in this study

Oil seperator	HTC	Manufacturer : Donghwa Win Model : DHO-22.2 Connection diameter : 7/8 in.
	LTC	Manufacturer : Temprite Model : 903 Connection diameter : 7/8 in.
Brine pump		Manufacturer : Speck Model : CY-6091-MK-HT(Q150) Range : 0-150 L/min Power consumption : 5.5kW
Receiver		Manufacturer : Donghwa Win Model : DHRV-075 Capacity : 9.2 L

Table 2.3 Specification of the measuring instruments used in this study

Flow meter	HTC	Manufacturer : ENDRESS HAUSER Model no. : PROMASS F 80F15-ACWSAAAABAAA Range : 0 ~ 1,300 L/h
	LTC	Manufacturer : ENDRESS HAUSER Model no. : PROMASS F 80F15-ACWSAAAABAAA Range : 0 ~ 1,300 L/h
	Coolant	Manufacturer : SMC Model no. : PF3W711-10-E-MR-X109 Range : 10 ~ 100 L/min
T-type thermocouple		Manufacturer : Daeyoung Sensor Type : T type

	Range : −270 ~ 400℃ Size : 1.6ϕ×10 cm
Power meter	Manufacturer : Yokogawa Mode no. : WT230 Range : Voltage, 15-600 V Current, 0.5-20 A
Data logger	Manufacturer : Yokogawa Mode no. : DR-232C Maximum input channels : 360 Maximum measurement interval : 300ch/500ms Maximum resolution : 1 μV (±20 mV)
Pressure transmitter	Manufacturer : Wika Mode no. : S-10 Range : 0 ~ 60 bar Connection : 1/2 PF

2.2 EXPERIMENTAL METHOD AND CONDITIONS

First, inject N_2 gas below the allowable pressure of the compressor for the leakage test of the experimental apparatus, and after a day passes, exhaust the N_2 gas and makes the inside of the system evacuated through the vacuum pump. After that, injects R-404A into the HTC, and R-23 into the LTC in a liquid state.

This experiment was carried out in the following order.

(1) Activate the condenser fan and brine pump.

(2) To prevent excessive pressure rise at the initial start of the LTC, first operates the HTC cycle.

(3) When the temperature of the brine cooled by a heat exchanger with HTC cycle becomes -25°C or less, the solenoid valve which flows to the cascade heat exchanger is opened. Then, give a time of 60 seconds to make the amount of refrigerant in the HTC entering the cascade sufficiently.

(4) After that, LTC compressor operates and closes the solenoid valve into the evaporator of the HTC and waits until the cascade refrigeration system is in a steady state.

(5) When the system is in a steady state, the brine temperature is controlled through the brine heater, and the flow rate of the refrigerant and the brine is controlled through the inverter by controlling the compressor rotation speed of HTC and LTC, the fan control of the condenser. After that, switching the HTC and LTC electronic expansion valve to the manual mode, and set to the

experimental conditions.

(6) If the temperature measurement variation of each system is within ± 0.5°C, the pressure measurement variation is within ± 0.01 Mpa, and the volumetric flow rate of the brine through the brine pump is within ± 0.2 L/min, the system is considered to steady state and measure for 20 minutes.

Table 2.1 shows the experimental conditions. The condensation temperature of the HTC, the condensation and evaporation temperature of the LTC were set as in Table 2.1. In order to analyze the optimum performance of the cascade refrigeration system, the measurement range of each condition was precisely set at 2°C.

Table 2.4 Test conditions for cascade refrigeration system

Parameter	Value	Unit
HTC condensation temperature	20 ~ 50	℃
LTC condensation temperature	-30 ~ 0	℃
LTC evaporation temperature	-80 ~ -50	℃
Temperature difference in cascade heat exchanger	10	℃
Subcooling degree	5	℃
HTC, LTC superheating degree	6	℃
Cooling capacity	10	kW
Refrigerant	R-404A / R-23	-
Charging amount of refrigerant	5 / 5	kg

2.3 DATA REDUCTION

REFPROP (version 8.0) [17], which is a refrigerant property calculation program developed by NIST, was used to calculate the thermal properties of R-404A and R-23 refrigerants used in this study. The following equation was used to analyze the performance characteristics of the cascade refrigeration system. First, to set the cooling capacity of the LCT evaporator to be 10 kW, the inlet and outlet temperatures of the brine and its corresponding density and specific heat value were calculated according to equation (2.1).

$$Q_{L,evap} = \int_{T_{b,out}}^{T_{b,in}} V_b \times \rho \times c_b dT \times \frac{1}{6 \times 10^{-7}} \tag{2.1}$$

The brine used in the experiment was the NOVEC^{TM} 7500 product, and the formula of brine density and specific heat were calculated by providing in 3M^{TM} [18]. The related equations are expressed in (2.2) and (2.3).

$$\rho\,[kg/m^3] = -2.0845 \times T[℃] + 1665.8 \tag{2.2}$$

$$c_b[J/kg \cdot K] = 1.4982 \times T[℃] + 1091 \tag{2.3}$$

The heat capacity of the cascade heat exchanger was calculated by the enthalpy difference between inlet and outlet of HTC, LTC refrigerant state point in the cascade heat exchanger. The related equation is shown in the following equation (2.4).

$$Q_{cas} = m \times \Delta h \tag{2.4}$$

Also, the HTC and LTC compressor power consumption was measured by a power meter. From power consumption and equation (2.1), the HTC, LTC, and overall coefficient of performance (COP) was calculated by the following equation (2.5) ~ (2.7).

$$COP_H = \frac{Q_{cas}}{W_{H,comp}} \tag{2.5}$$

$$COP_L = \frac{Q_{L,evap}}{W_{L,comp}} \tag{2.6}$$

$$COP_O = \frac{Q_{L,evap}}{W_{H,comp} + W_{L,comp}} \tag{2.7}$$

CHAPTER 3. EXPERIMENTAL RESULTS

3.1 PERFORMANCE CHARACTERISTICS

In this chapter, the inverter frequency of the compressor, and the brine pump, the temperature and flow rate of the brine, and the ambient, and the opening rate of the expansion valve are adjusted to set the experimental conditions in Section 2.2. Then, the performance characteristics of the cascade refrigeration system were experimentally analyzed.

3.1.1 Effect of condensation temperature of HTC

Table 3.1 shows the experimental conditions for analyzing the performance characteristics of the cascade refrigeration system according to the HTC condensation temperature.

Table 3.1 Test conditions for cascade refrigeration system according to condensation temperature of HTC

Parameter	Value	Unit
HTC condensation temperature	20 ~ 50	℃
LTC condensation temperature	-20	℃
LTC evaporation temperature	-50, -60, -70, -80	℃
Temperature difference in cascade heat exchanger	10	℃
Subcooling degree	5	℃
HTC, LTC superheating degree	6	℃
Cooling capacity	10	kW
Refrigerant	R-404A / R-23	-
Charging amount of refrigerant	5 / 5	kg

(1) Refrigerant mass flow rate

Fig. 3.1 and Fig. 3.2 is a graph showing the refrigerant mass flow rate of the HTC and LTC according to the condensation temperature change of the HTC. Similar tendency can be found in the researchers conducted by Parekh et al. [2], and Kasi [5]. As the condensation temperature of HTC increases, the flow rate of HTC refrigerant tends to increase. It means that as the condensation temperature of the HTC increases, the flow rate increases to maintain the target superheating degree due to the decrease of the volume efficiency. On the other hand, the LTC refrigerant mass flow rate does not change significantly, because the state point of each element at the LTC part does not change that much. When the evaporation temperature of the LTC decreases under the same experimental conditions, both the refrigerant flow rate at the HTC and LTC increases. The reason for this will be mentioned in Section 3.1.2.

(2) Heat capacity of cascade heat exchanger

Fig. 3.3 shows the heat capacity of the cascade heat exchanger according to the variation of the condensation temperature at the HTC. The heat capacity value of the cascade heat exchanger is almost constant even when the condensation temperature of the HTC is changed because there is not a significant change in the refrigerant state point of the HTC evaporation part. In the same experimental conditions, when the evaporation temperature of the LTC decreases, the heat capacity of the cascade heat exchanger increases, which will also be mentioned in Section 3.1.2.

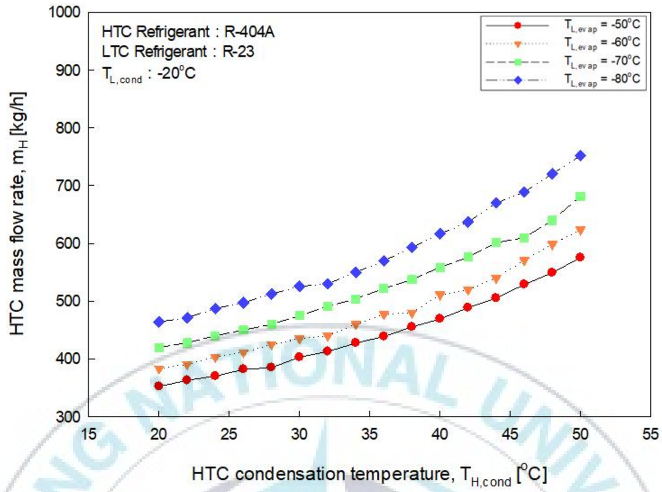

Fig. 3.1 Refrigerant mass flow rate of HTC according to HTC condensation temperature

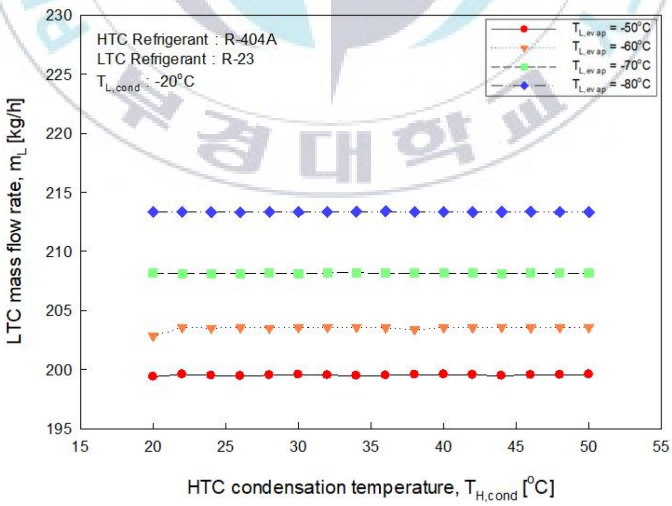

Fig. 3.2 Refrigerant mass flow rate of LTC according to HTC condensation temperature

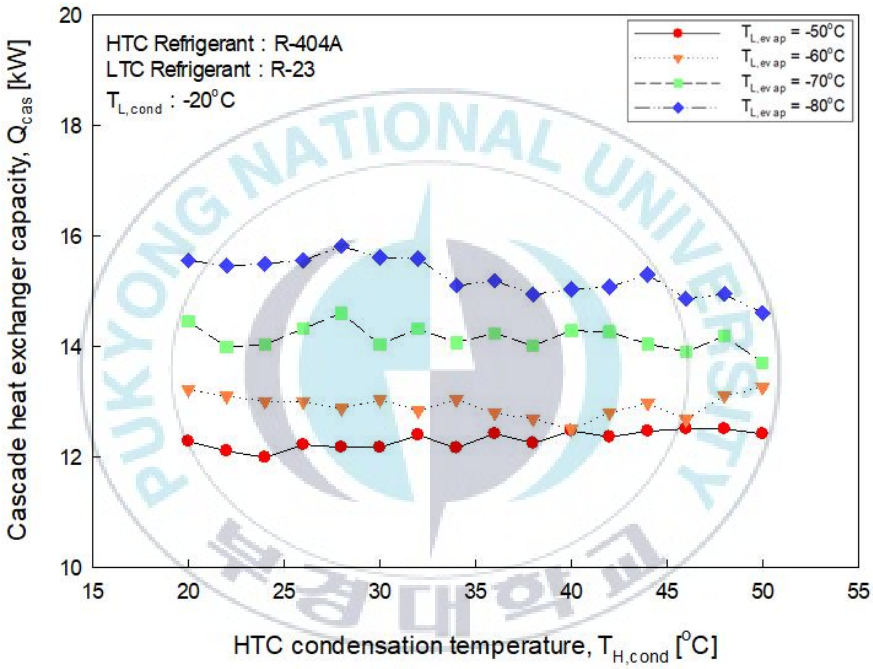

Fig. 3.3 Cascade heat exchanger capacity according to HTC condensation temperature

(3) Power consumption of compressor

Fig. 3.4 is a graph showing the power consumption of the compressor at the HTC and LTC according to the condensation temperature change at the HTC. Analogous trends were presented in the studies that were carried out by Kasi [5]. As the condensation temperature of HTC increases, the power consumption of compressor at HTC tends to increase. It is because the compression ratio, which is the difference between the evaporation pressure and the condensation pressure of the HTC, is increased. On the other hand, the power consumption of the compressor at the LTC is almost constant, which is the result that the state point of the LTC is almost constant as mentioned above.

(4) Discharge temperature

Fig. 3.5 shows the discharge temperature at the HTC and LTC according to the condensation temperature change at the HTC. As the temperature of condensation increases in the HTC, the HTC discharge temperature tends to increase, and it is also affected increment of the compression ratio. On the other hand, the discharge temperature at the LTC shows a constant tendency. It seems to result from the fact that the conditions of the LTC are almost the same. When the evaporation temperature of the low temperature is decreased under the same experimental conditions, the temperature of the discharged gas remains practically constant at the HTC, but the discharge temperature increases at the LTC due to the increase of the compression ratio.

(5) COP

Fig. 3.6 is a graph showing the COP of the HTC and LTC according to the condensation temperature change of the HTC. Similar trends were presented in the studies that were carried out by Kilicarslan et al. [1], Parekh et al. [2], and Kasi [5]. In Fig. 3.6, COP at HTC tends to decrease as the condensing temperature of HTC because compressor power consumption is increased due to the compression ratio. On the other hand, the COP at the LTC shows a constant tendency because the pressure and the temperature do not change that much. Therefore, the COP of the HTC tends to decrease, and the COP of the LTC tends to be constant, so in Fig. 3.7, overall COP tends to decline tendency.

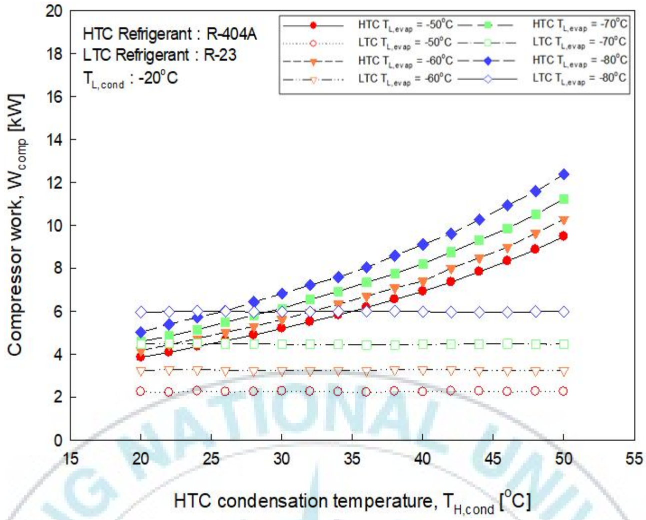

Fig. 3.4 Power consumption of HTC, LTC compressor according to HTC condensation temperature

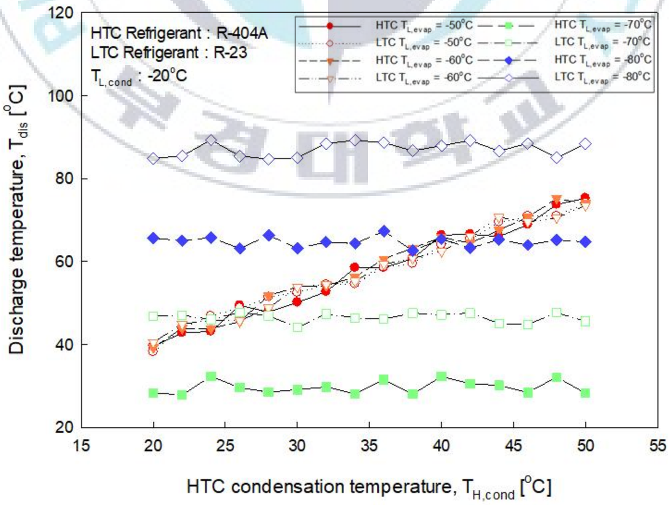

Fig. 3.5 Discharge temperature of HTC, LTC according to HTC condensation temperature

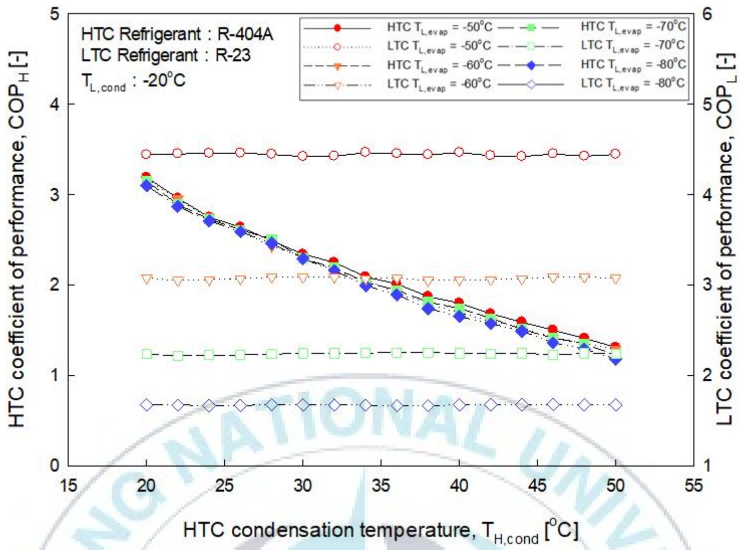

Fig. 3.6 COP of HTC, LTC according to HTC condensation temperature

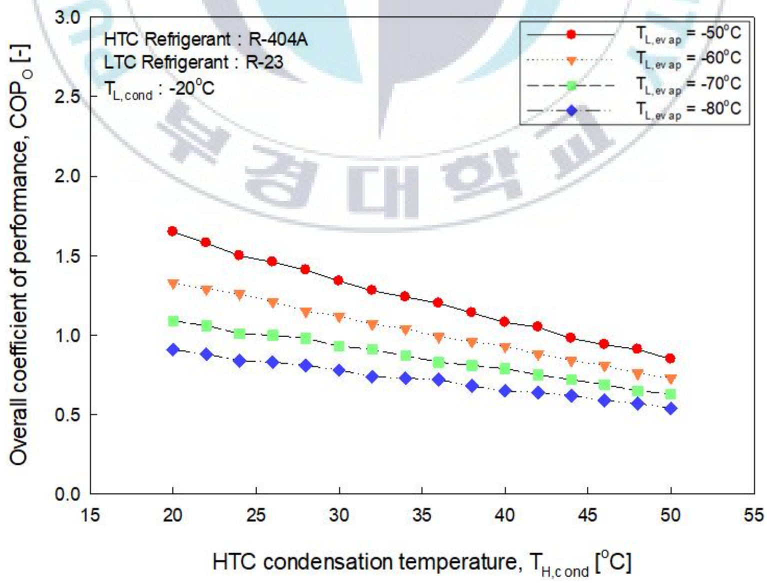

Fig. 3.7 Overall COP according to HTC condensation temperature

3.1.2 Effect of evaporation temperature of LTC

Table 3.2 shows the experimental conditions for analyzing the performance characteristics of the cascade refrigeration system according to the LTC evaporation temperature.

Table 3.2 Test conditions for cascade refrigeration system according to evaporation temperature of LTC

Parameter	Value	Unit
HTC condensation temperature	20, 30, 40, 50	℃
LTC condensation temperature	-20	℃
LTC evaporation temperature	-50 ~ -80	℃
Temperature difference in cascade heat exchanger	10	℃
Subcooling degree	5	℃
HTC, LTC superheating degree	6	℃
Cooling capacity	10	kW
Refrigerant	R-404A / R-23	-
Charging amount of refrigerant	5 / 5	kg

(1) Refrigerant mass flow rate

Fig. 3.8 and Fig. 3.9 shows the refrigerant mass flow rate at the HTC and the LTC according to the evaporation temperature change at the LTC. This results have simillar tendency in the researchers conducted by Parekh et al. [2], and Kasi [5]. As the evaporation temperature of the LTC increases, the refrigerant mass flow rates tend to decrease at the HTC, and LTC. It is because the enthalpy difference between the inlet and out of the LTC evaporator increases as the evaporation temperature increases, so the refrigerant mass flow rate decreases to achieve the same cooling capacity of 10 kW. It leads to a decrease the heat capacity in the cascade heat exchanger, and so the refrigerant mass flow rate at the HTC decreases. When the condensation temperature of the HTC changes under the same experimental conditions, the refrigerant mass flow rate at the HTC tends to increase, and the refrigerant mass flow rate at the LTC does not differ significantly as the condensation temperature of HTC increases.

(2) Heat capacity of cascade heat exchanger

Fig. 3.10 is a graph showing the heat capacity of the cascade heat exchanger according to the evaporation temperature change at low temperature. As the LTC evaporation temperature increases, the refrigerant flow rate at the LTC decreases as mentioned above, which causes the decrease of the heat quantity of the cascade heat exchanger. Therefore, the experimental results show that the heat capacity of cascade heat exchanger decreases. When the condensation temperature of the HTC changes under the same experimental conditions, the heat capacity of cascade heat exchanger shows almost constant value.

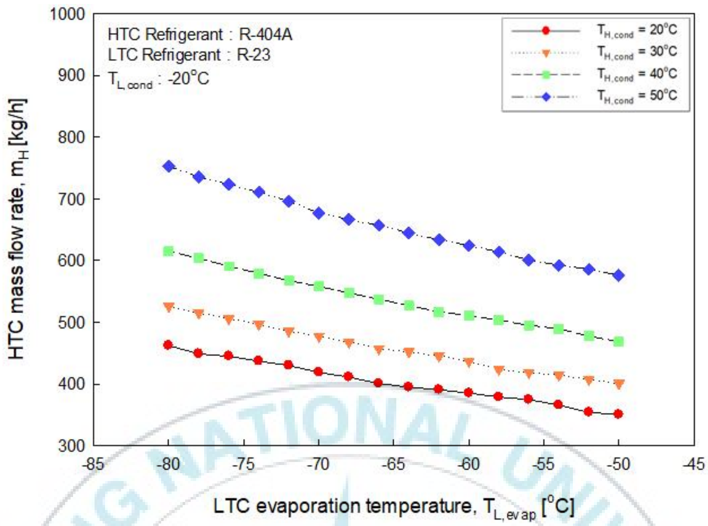

Fig. 3.8 Refrigerant mass flow rate of HTC according to LTC evaporation temperature

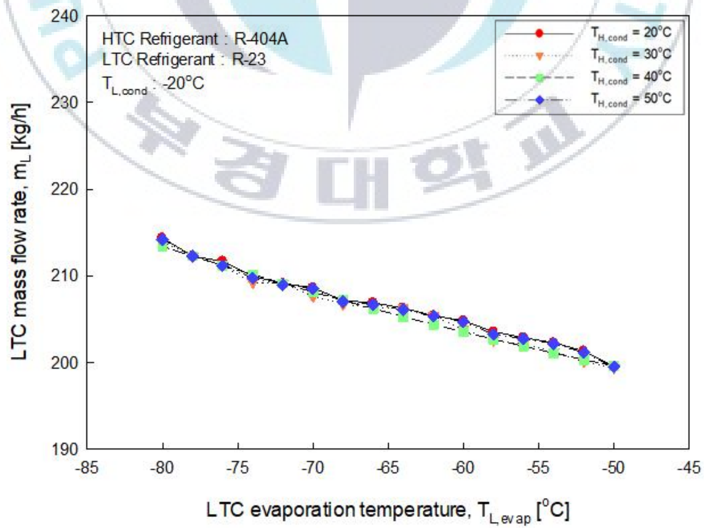

Fig. 3.9 Refrigerant mass flow rate of LTC according to LTC evaporation temperature

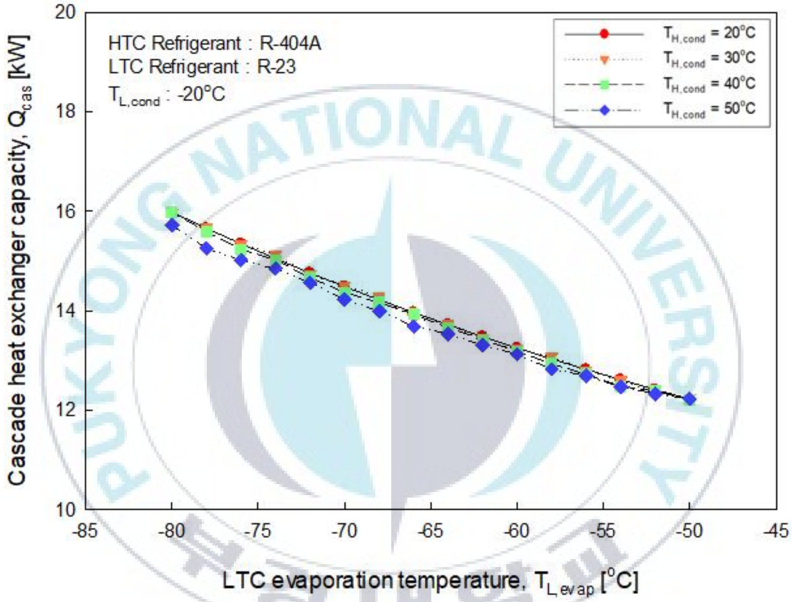

Fig. 3.10 Cascade heat exchanger capacity according to LTC evaporation temperature

(3) Power consumption of compressor

Fig. 3.11 shows the power consumption of the compressor at the HTC and LTC according to the evaporation temperature change at the LTC. Similar tendency can be found in the researchers conducted by Kasi [5]. As the evaporation temperature of the LTC increases, the power consumption of the compressor at HTC and LTC tends to decrease. This tendency appears as the refrigerant mass flow rate at the HTC and LTC reduces. When the condensation temperature of HTC changes under the same experimental conditions, the compression power of HTC tended to increase, which is a result of the high compression ratio of HTC. In the case of the LTC, the state point of LTC is constant, so the power consumption of LTC compressor shows almost the same value.

(4) Discharge temperature

Fig. 3.12 is a graph showing the discharge temperature at the HTC and LTC according to the evaporation temperature change at the LTC. As the evaporation temperature of LTC increases, the discharge gas temperature of the HTC tends to be almost constant. It is considered that the pressure and temperature value of each element of the HTC are kept almost constant; only the refrigerant flow rate of HTC decreases. On the other hand, the discharge gas temperature at LTC tends to decrease. It is considered to be because of the compression ratio, the volume efficiency of the compressor, and the compression efficiency decrease as the evaporation temperature decreases. When the condensation temperature of the high temperature increases under the same experimental conditions, the discharge temperature of HTC tended to increase, and the discharge temperature of LTC showed an almost constant result.

(5) COP

Fig. 3.13 is a graph showing the COP of the HTC and LTC according to the evaporation temperature change of LTC. Analogous trends were presented in the studies that were conducted by Kilicarslan et al. [1], Parekh et al. [2], Kasi [5]. As shown in Fig. 3.13, as the evaporation temperature of the LTC increases, the COP of HTC tends to be almost constant. It is also because the temperature and pressure of each element of the HTC are hardly changing. On the other hand, the COP at low temperatures tended to increase. It is considered that the compression ratio at the LTC becomes smaller as the evaporation temperature increases, and the volume efficiency and the compression efficiency increase. When the condensation temperature of the LTC (the temperature in the cascade heat exchanger)is kept constant, As in Fig. 3.14, the overall COP tends to increase, which is considered to be due to the increase in LTC COP.

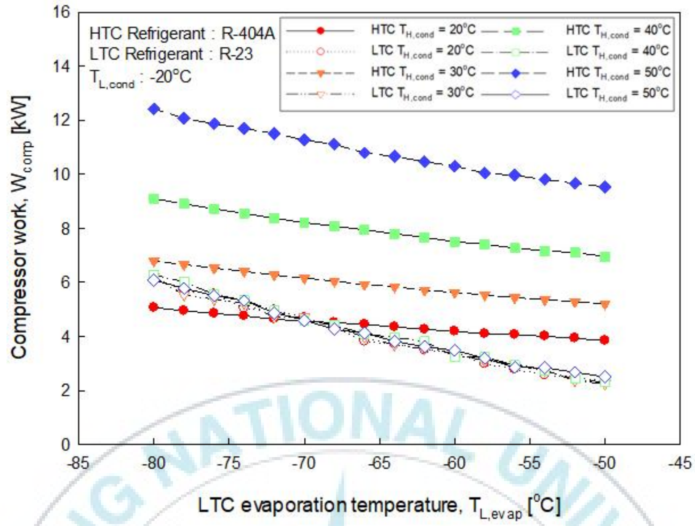

Fig. 3.11 Power consumption of HTC, LTC compressor according to LTC evaporation temperature

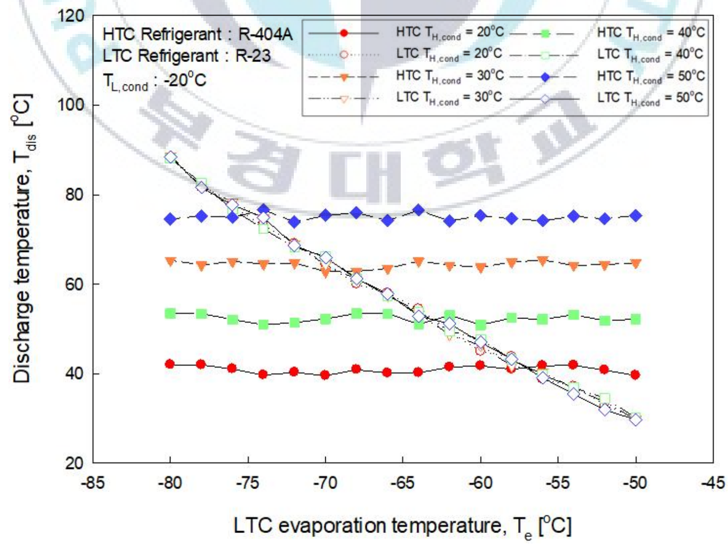

Fig. 3.12 Discharge temperature of HTC, LTC according to LTC evaporation temperature

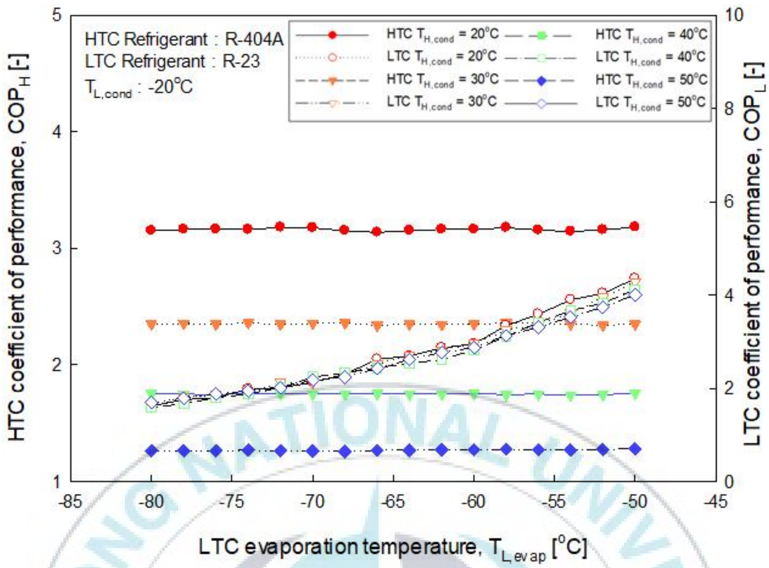

Fig. 3.13 COP of HTC, LTC according to LTC evaporation temperature

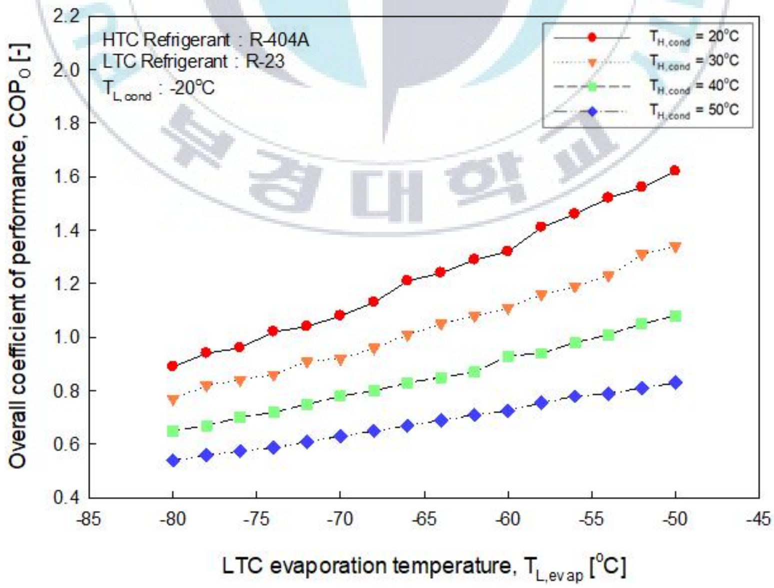

Fig. 3.14 Overall COP according to LTC evaporation temperature

3.1.3 Effect of condensation temperature of LTC

Table 3.3 shows the experimental conditions to analyze the performance characteristics of the cascade refrigeration system according to the LTC condensation temperature.

Table 3.3 Test conditions for cascade refrigeration system according to condensation temperature of LTC

Parameter	Value	Unit
HTC condensation temperature	30	℃
LTC condensation temperature	20 ~ 50	℃
LTC evaporation temperature	-50 ~ -80	℃
Temperature difference in cascade heat exchanger	10	℃
Subcooling degree	5	℃
HTC, LTC superheating degree	6	℃
Cooling capacity	10	kW
Refrigerant	R-404A / R-23	-
Charging amount of refrigerant	5 / 5	kg

(1) Refrigerant mass flow rate

Fig. 3.15 and Fig. 3.16 shows the refrigerant mass flow rate at the HTC and LTC according to the condensation temperature change at LTC. This tendency is simillar with the reasearchers conducted by Parekh et al. [2], and Sun et al [3]. As the temperature of the LTC condensation temperature increases, the refrigerant mass flow rate at the LTC increases. It is because the compression ratio of the LTC increases as the condensation temperature of LTC increases, so the LTC refrigerant mass flow rate increased. As a result, the heat capacity of the cascade heat exchanger increases, and the refrigerant mass flow rate at the HTC also tends to increase. In the same experimental conditions, the refrigerant flow rate at HTC and LTC tends to increase gradually as the evaporation temperature gets lower when the LTC evaporation temperature was changed. It is because a larger compression ratio becomes more significant at lower evaporation temperature.

(2) Heat capacity of cascade heat exchanger

Fig. 3.17 is a graph showing the heat capacity of the cascade heat exchanger according to the change of the condensation temperature at LTC. As the condensation temperature of the LTC increases, the compression ratio of LTC increases, and the refrigerant flow rate of LTC increases, which causes the increase of the heat quantity of the cascade heat exchanger. As a result, the heat capacity of the cascade heat exchanger tends to increase. In the same experimental conditions, when the LTC evaporation temperature is changed, it is considered that the lower the evaporation temperature is, the higher the refrigerant flow rate of the system, the higher the heat capacity of the cascade heat exchanger.

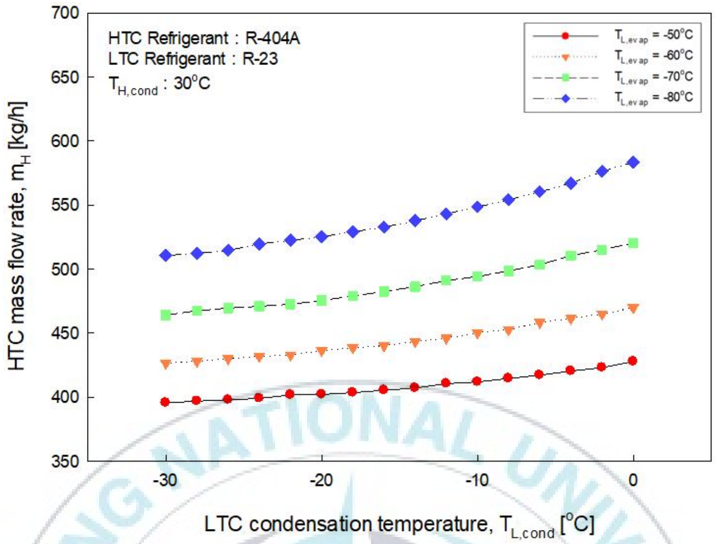

Fig. 3.15 Refrigerant mass flow rate of HTC according to LTC condensation temperature

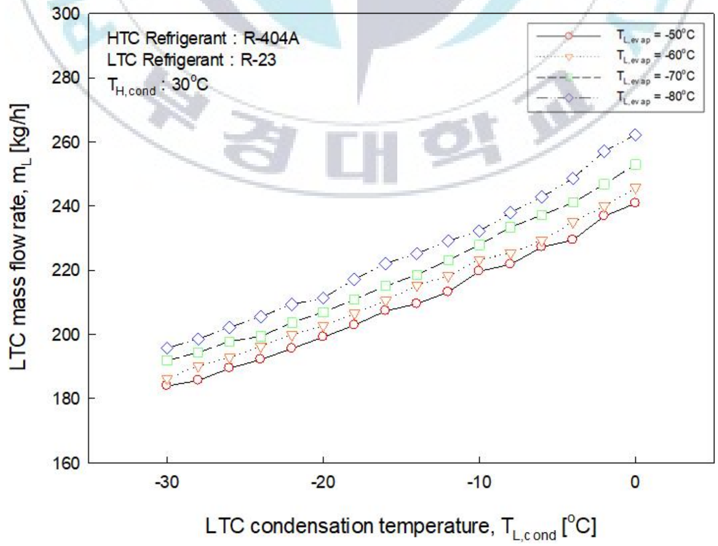

Fig. 3.16 Refrigerant mass flow rate of LTC according to LTC condensation temperature

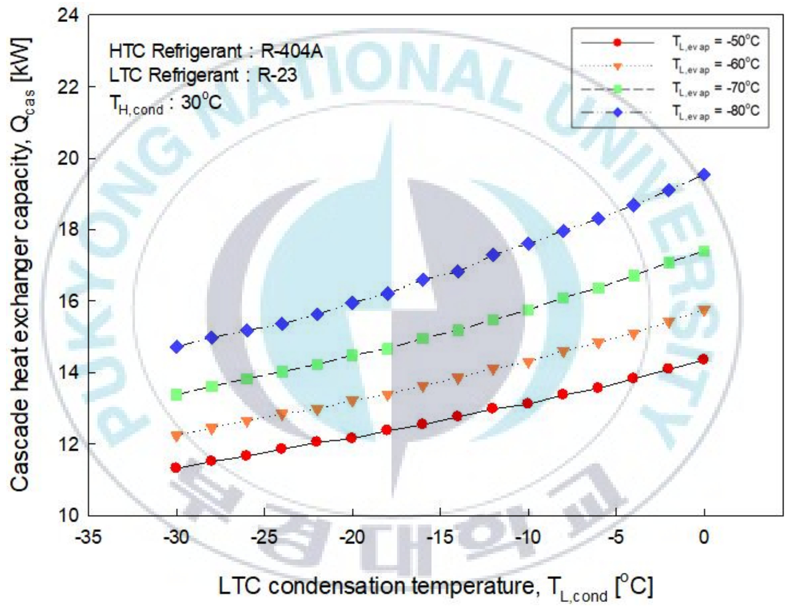

Fig. 3.17 Cascade heat exchanger capacity according to LTC condensation temperature

(3) Power consumption of compressor

Fig. 3.18 is a graph showing the power consumption of the compressor at the HTC and LTC according to the variation of the condensation temperature at LTC. In the case of the LTC, the compressor power consumption tends to increase as the condensation temperature of LTC increases. It is because of the increment of the LTC compression ratio. However, the power consumption of HTC tends to decrease, which is the result of the compression ratio of the HTC decreases as the temperature and pressure of the refrigerant entering the cascade heat exchanger increases. When the evaporation temperature of the LTC decreases under the same experimental conditions, the LTC compressor power tends to increase. As in Fig. 3.17, it appears to be due to an increase in the refrigerant flow rate and the compression ratio.

(4) Discharge temperature

Fig. 3.19 shows the discharge temperature at the HTC and LTC according to the condensation temperature change at LTC. As the condensation temperature of the LTC increases, the discharge gas temperature of the HTC tends to decrease, and the discharge temperature of LTC tends to increase. This result is related to the compression ratio. It is considered that when the condensation temperature of the LTC rises, the compression ratio of the HTC system decreases, and the LTC system increases. However, as the evaporation temperature of LTC decreases under the same experimental conditions, the discharge temperature of the LTC gradually increases, but the HTC shows a constant tendency. This results are simiilar with Sun et al. [3]

(5) COP

Fig. 3.20 shows the COP of the HTC and LTC according to the change of the LTC condensation temperature. Analogous trends were presented in the studies that were carried out by Parekh et al. [2], and Sun et al. [3]. As shown in Fig. 3.20, as the condensation temperature of the LTC increases, the COP of HTC increases, and LTC decreases. In the case of the LTC COP, as the power consumption of compressor increases, it tends to decrease compared to the same cooling capacity of 10 kW. The COP of the HTC increases with the increase of the LTC condensation temperature. It is because the heat capacity of the cascade heat exchanger increases, and the power consumption of the compressor decreases. Therefore, the overall COP results are shown in Fig. 3.21. The overall COP of the cascade refrigeration system tends to increase with increasing the LTC condensation temperature then decrease at a specific point. It is because the sum of the power consumptions of the LTC and HTC compressor become larger than the cooling capacity at a particular temperature. It means that there is a specific LTC condensation temperature that has the maximum overall COP. As can be seen from Fig. 3.21, it can be seen that it has different values depending on each evaporation temperature.

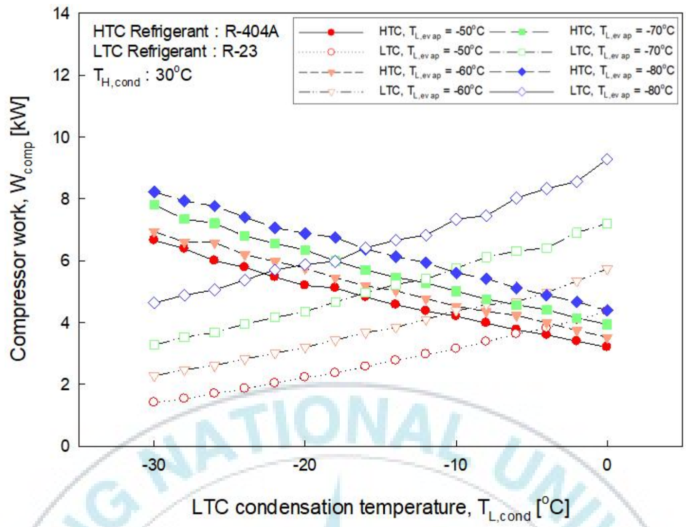

Fig. 3.18 Power consumption of HTC, LTC compressor according to LTC condensation temperature

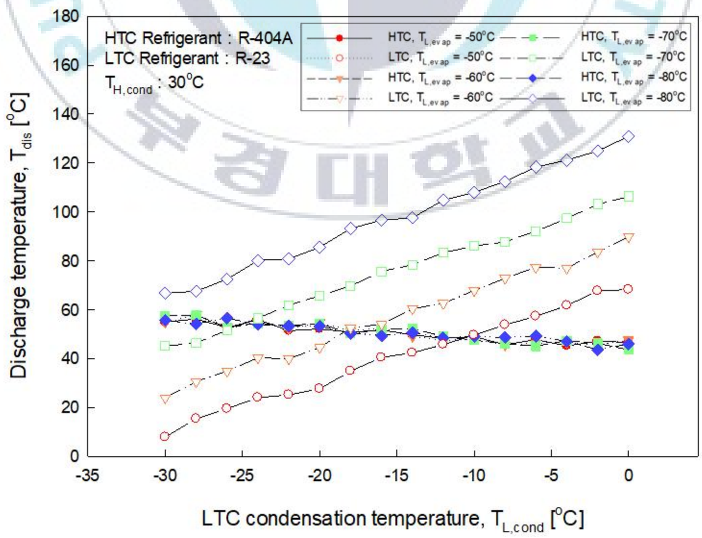

Fig. 3.19 Discharge temperature of HTC, LTC according to LTC condensation temperature

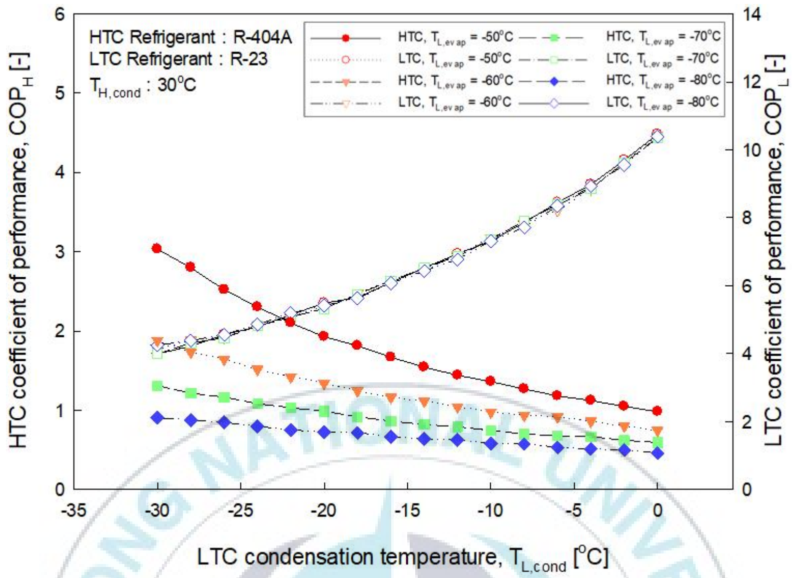

Fig. 3.20 COP of HTC, LTC according to LTC condensation temperature

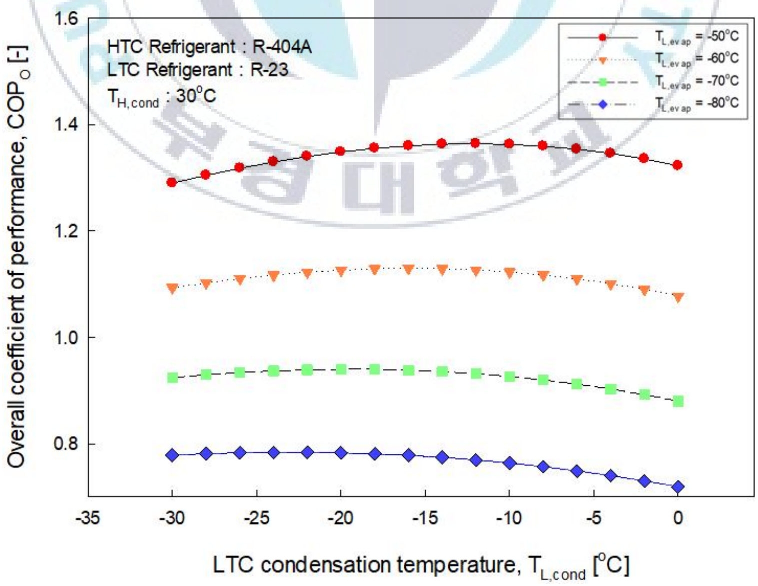

Fig. 3.21 Overall COP according to LTC condensation temperature

3.2 OPTIMUM OPERATING CONDITION

3.2.1 Optimum operating condition of cascade refrigeration system

In Section 3.1.3, there is an LTC condensation temperature with the maximum COP of each cascade refrigeration system when the evaporation temperature changes. In Section 3.2, the optimum operating conditions are summarized by integrating the condensation temperature of the HTC and the condensation temperature of the LTC which can affect the system according to the desired operating temperature range when designing and operating the actual system. The results are shown in Table 3.4.

Table 3.4 Optimum condensation temperature of LTC for R-404A/R-23 cascade refrigeration system

Data table [℃]		$T_{L,evap}$ [℃]							
		-50	**-52**	**-54**	**-56**	**-58**	**-60**	**-62**	**-64**
$T_{H,cond}$ [℃]	**20**	-18	-18	-20	-20	-20	-22	-22	-24
	22	-16	-18	-18	-18	-20	-20	-22	-22
	24	-16	-16	-16	-18	-18	-20	-20	-20
	26	-14	-16	-16	-16	-18	-18	-18	-20
	28	-14	-14	-14	-16	-16	-16	-18	-18
	30	-12	-12	-14	-14	-16	-16	-16	-18
	32	-12	-12	-12	-14	-14	-14	-16	-16
	34	-10	-10	-12	-12	-12	-14	-14	-14
	36	-8	-10	-10	-10	-12	-12	-12	-14
	38	-8	-8	-8	-10	-10	-12	-12	-12
	40	-6	-8	-8	-8	-10	-10	-10	-12
	42	-6	-6	-6	-8	-8	-8	-10	-10
	44	-4	-4	-6	-6	-6	-8	-8	-8
	46	-2	-4	-4	-4	-6	-6	-6	-8
	48	-2	-2	-2	-4	-4	-4	-6	-6
	50	0	0	-2	-2	-2	-4	-4	-4

Data table [℃]		$T_{L,evap}$ [℃]							
		-66	**-68**	**-70**	**-72**	**-74**	**-76**	**-78**	**-80**
$T_{H,cond}$ [℃]	**20**	-24	-24	-26	-26	-28	-28	-28	-30
	22	-22	-24	-24	-26	-26	-26	-28	-28
	24	-22	-22	-24	-24	-24	-26	-26	-26
	26	-20	-22	-22	-22	-24	-24	-24	-26
	28	-20	-20	-20	-22	-22	-22	-24	-24
	30	-18	-18	-20	-20	-20	-22	-22	-24
	32	-16	-18	-18	-18	-20	-20	-22	-22
	34	-16	-16	-16	-18	-18	-20	-20	-20
	36	-14	-14	-16	-16	-18	-18	-18	-20
	38	-14	-14	-14	-16	-16	-16	-18	-18
	40	-12	-12	-14	-14	-14	-16	-16	-16
	42	-10	-12	-12	-12	-14	-14	-14	-16
	44	-10	-10	-10	-12	-12	-12	-12	-14
	46	-8	-8	-10	-10	-10	-10	-12	-12
	48	-6	-8	-8	-8	-8	-10	-10	-10
	50	-6	-6	-6	-6	-8	-8	-8	-10

CHAPTER 4. CONCLUSIONS

In this study, the performance characteristics of the cascade refrigeration system with R-404 at HTC and R-23 at LTC were investigated by experiment in terms of the condensation temperature at HTC, condensation temperature, and evaporation temperature at LTC. The results are summarized as follows.

(1) As the condensation temperature of the HTC increases, the COP of the HTC is lowered, and LTC is almost constant. As a result, the overall COP tends to decrease, which is considered to have been strongly influenced by HTC.

(2) As the evaporation temperature of the LTC increases, the COP of the HTC is almost constant, but the COP of LTC tends to increase. As a result, the overall COP tends to increase, which is significantly affected by the LTC.

(3) As the condensation temperature of the LTC increases, the COP of HTC is lowered, and LTC increases. As a result, the overall COP tended to rise and decrease to the LTC condensation temperature. It means there is a specific LTC condensation temperature, which has a maximum overall COP. So finally, the optimum operating conditions of a cascade refrigeration system with R-404A and R-23 according to the target temperature are summarized with experimental results of the evaporation temperature of the HTC and the evaporation temperature of the LTC.

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ACKNOWLEDGEMENT

2년간의 석사 과정을 마치면서 전공에 대한 지식 뿐 아니라 삶의 지혜를 많이 배울 수 있는 시간이 된 것 같습니다. 처음 신소재공학과 학부를 졸업하고 관련 전공과 상이한 냉동공조공학과의 대학원을 선택하기는 쉽지 않았습니다. 하지만 많은 분들의 조언과 도움이 있었기 때문에 석사 과정을 무사히 마치지 않았나 생각하면서 이 장을 빌려 감사의 말씀을 전합니다.

먼저, 2년 동안 많은 배움의 기회를 주시고 다방면으로 챙겨주시며 본 논문이 완성될 수 있게 도움을 주신 존경하는 손창효 교수님께 정말 감사드립니다. 그리고 타지에서 생활하는 저에게 따뜻한 말씀으로 많은 격려와 위로를 해주신 윤정인 교수님께 감사드립니다. 또한 대학원 수업 및 석사 세미나를 통하여 저의 부족한 지식을 일깨워주신 김종수 교수님, 금종수 교수님, 최광환 교수님, 정석권 교수님, 김은필 교수님께 머리 숙여 감사의 말씀을 전합니다.

이외에도 석사 과정을 마치는 동안 많은 분들께 도움을 받았습니다. 연구 과제를 진행하는 동안 장치와 실험에 관련 되서 물심양면으로 도와주신 ENRESYS 모임의 대선배이신 설원실 박사님, 실험을 진행하는 동안 모르는 점을 항상 친절하고 자세하게 알려주신 문춘근 박사님, 실험실에 잘 적응할 수 있게 도와주신 하수정 박사님, 전민주 박사님, 후배를 위해 많은 조언을 해주신 이근태 선배님께 감사의 말씀 전합니다.

2년간 실험실 생활을 하며 나이는 어리지만 선배의 위치로써 많은 것을 알려주고 졸업한 성현이와 현경이, 힘들 때마다 많은 힘이 되어준 대호, 같은 시기에 연구실 생활을 시작하며 도움을 준 용기, 졸업학기에 들어와서 많이 챙겨주지 못했지만 언제나 잘 따라준 상우, 남욱, 동익씨,

그리고 지금은 없지만 밤에 혼자 남았을 때 옆에서 말벗이 되어준 용택이한테 감사의 말씀을 전합니다. 또한 실험실은 다르지만 술 한잔 하며 많은 조언을 해주신 김민수 박사님, 언제나 웃음으로 맞아주신 휘웅이 형, 같이 연구 과제를 진행하며 많은 얘기를 나눈 광석, 지훈, 두영, 선근, 준영, 지후에게도 감사의 말씀을 전합니다. 행정업무를 볼 때마다 항상 친절하고 자세하게 알려주신 냉동공조공학과를 위해 일해주시는 김대한 조교님, 장지영 선생님께도 감사의 말씀을 드립니다. 또한, 힘들 때마다 언제든 터놓고 얘기할 수 있게 해준 어릴 때부터 친하게 지내왔던 무찬이, 학부 때부터 친하게 지냈던 병호, 도현이, 타지에서 고생하는 저를 항상 따뜻하게 챙겨주는 아름이에게도 감사의 말씀을 전합니다.

마지막으로 이 세상 그 어떠한 말로도 표현을 할 수 없이 큰 사랑을 주시고 언제나 집안의 장남을 이해해주시고 믿어주시는 우리 부모님, 부족한 형을 잘 따라주는 애교쟁이 동생 준호에게 너무나 큰 감사를 드립니다.

석사 과정을 지나 이제는 박사 과정 진학을 앞두고 있습니다. 힘든 과정이 되겠지만, 많은 격려와 조언을 주신 분들의 감사함을 생각하며 한층 더 나은 사람이 되도록 노력하고, 더 나아가 세계적으로 이름을 떨칠 수 있는 냉동공조인이 되도록 하겠습니다. 다시한번 도움을 주신 많은 분들께 머리 숙여 감사의 말씀을 전합니다.

2019년 8월

이준혁 올림