

Evaluation on the cooling capacity of a cascade freezing system using refrigerant pair R513A/R744

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Abstract

This paper was studied in a cascade system using a pair of refrigerants with R513A/R744, it was an experimental methodology. The R744 refrigerant was used for low stage cycle and R513A refrigerant was used for high stage cycle. The experimental data was collected at the ambient temperature of 32°C. In this study, the thermodynamic parameters of those refrigerants in the cascade system were indicated detailly, the temperature of cold storage was gone from 32°C down to -20°C in 35 minutes. With the R744 refrigerant in low stage cycle has condensing temperature is 5.9°C and evaporating temperature is -25°C, the cooling capacity of system is 1.35 kW and the coefficient of performance is 2. In other that, those theory results are suitable for an experimental data, the differential is less than 10%.

Key: cooling capacity, cascade, R513A/R744, freezing, refrigerant.

1.0 INTRODUCTION

Nowadays, refrigeration systems use refrigerants are CFCs (Chlorofluorocarbons) and HCFCs (Hydrochlorofluorocarbons) which contain chlorine atoms. When there is a leak, the medium gradually flies to the upper atmosphere, causing a greenhouse effect and the impact of penetrating the Earth's ozone layer, thereby changing the global climate. Therefore, some refrigerants that have little impact on climate change and environmental protection have been selected to replace chlorine atom-containing media in some refrigeration systems. With the use of the new refrigerant R513A, this is also one of the mediums with the potential not to deplete the ozone layer (OPD=0) and the global warming index is very low (GWP=573). R513A is suitable as a replacement for R134a with excellent efficiency in new systems, providing very high energy efficiency and environmental sustainability. Ming et al. [1] performed a performance evaluation and analysis of the optimal configuration of CO₂/NH₃ cascade refrigeration system with a Membrane Condensation – Evaporation unit. The results of the thermodynamic analysis of the system show an improvement in the coefficient of efficiency (COP) due to the small temperature difference provided by the cascade heat exchanger. Logesh et al. [2] successfully analyzed the performance of a cascade refrigeration cycle (CRS) with three different pairs of mediums: R134a/R23, R410A/R23, R404A/R170 in the superheat range of 10°C and supercold 5°C. The results showed that the R134a/R170 pair had a greater COP and lower mass flow in the study pairs. Next, Getu and Bansal [3] conducted a thermodynamic analysis of the R744/R717 carbon dioxide–ammonia bed coupled refrigeration system to optimize the design and operation parameters of the system. As a result, when the condensate temperature increases, the COP decreases and the refrigerant flow rate increases. As the evaporation temperature increases, the COP of the donation system and the flow rate decreases. When the superheat increases, the mass flow rate increases but the COP decreases, and when the evaporation temperature increases, both the mass flow rate and the COP increase. The temperature difference in the stratified condenser increases resulting in a decrease in the mass flow rate and the COP of the system. Gautam et al. [4] conducted a subcritical to supercritical analytical study for evaporators with temperatures ranging from -5°C to 15°C. For the subcritical cycle, the steam generator and condenser temperature ranged from 65°C to 91°C to 20°C to 30°C, and for the upper critical cycle, steam generators and coolers are varied from 90°C to 120°C and 35°C to 40°C, respectively. The maximum COP and specific cooling efficiency (SCE) are achieved by combining both heat recovery and mass for the base cycle of 0.305 and 105 kJ/kg. In the subcritical cycle, COP efficiency improves from 38% to 77%, while in the upper critical cycle it is about 17% to 75%. Regarding the CO₂/R32 heat pump system, Sun et al. [5] conducted a study to evaluate the cooling

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and heating performance as well as compressor operating conditions of the CO₂/R32 water heat pump system. Heating efficiency (COP_h) and cooling efficiency (COP_c) results improved by up to 23.3% and 65.2% in heating capacity, cooling capacity and thrust pressure of CO₂/R32 compressors were significantly reduced.

Regarding the comparison of the performance of the laminated refrigeration system compared to the HFC two-stage refrigeration system, Messineo [6] conducted an evaluation of the performance of the R744/R717 laminated refrigeration system compared to the HFC two-stage refrigeration system. The results show that the laminated refrigeration system is a good alternative in terms of energy, safety and environment compared to the R404A two-stage refrigeration system for low evaporation temperatures (-30°C ÷ -50°C) in commercial refrigeration. Zhang et al. [7] conducted a theoretical evaluation of the efficiency of internal heat exchangers in the critical CO₂ cooling cycle using ejectors. The results show that the suction rate and ejector efficiency increase, and the recovery pressure decreases under the same cooling gas pressure condition. Manjili and his colleagues [8] used Engineering Equation Solver (EES) software to analyze the thermodynamics and exergetics of the CO₂ refrigeration cycle on a 2-stage critical threshold using 2 ejectors, the steam compression process is carried out in 2 stages, each steam compression line consists of a separate ejector. The results showed that COP improved by 20% - 80% compared to the usual cycle. Liu et al. [9] analyzed the thermodynamics of the above-critical CO₂ refrigeration cycle with an integrated thermoelectric supercooler and ejector to compare it with two independent above-critical CO₂ cycles: (1) with the thermoelectric supercooler and (2) with the ejector. The results indicate the maximum cooling efficiency of the performance achieved for the integrated cycle with the same optimization of the cold temperature and discharge pressure. The efficiency of the integrated cycle increased by 39.34% corresponding to an 8.01% decrease in discharge pressure under the operating conditions of 5°C evaporation temperature and external cooling temperature of 40°C. Nakagawa et al. [10] experimentally analyzed the effect of the internal heat exchanger of the CO₂ refrigeration cycle on the critical 2-stage ejector and compared it to a conventional refrigeration system. The experiment was carried out at different operating pressures and temperatures for 3 cases: without internal heat exchanger, 30 cm internal heat exchanger, 60 cm internal heat exchanger. The results showed that the nozzle system with 60 cm of internal heat exchanger had the largest COP increase by 27% compared to the conventional system. Dang and his colleagues [11] conducted a COP study of a CO₂ air conditioning system with a minichannel evaporator using subcooling. Without subcooling process, the COP is close to 1.59; it is lower than the conventional air conditioning system. During the subcooling process, the COP reached 4.97 at a cooling pressure of 77 bar and an evaporation temperature of 15°C, which was higher than other published results. Nguyen and Dang [12] studied the effect of flow on the efficiency of micro evaporation channels using CO₂ refrigerant. CO₂ air conditioning is operated under an ambient temperature of 30.5°C. While the flow rate increases from 109.6 to 116.2 kg/hr, the COP increases slightly from 4.2 to 5.15 and when the flow rate increases to 117.4 and 121.4 kg/hr, the COP increases significantly from 5.45 to 7.9. In addition, the output temperature of the cooler increases from 32.3 to 36.50°C, the COP drops sharply from 7.9 to 4.2. Nguyen and his colleagues [13] conducted an experiment with an air conditioning system with a copper heat exchanger. In this study, the compressor and cooler were tested using a hydraulic method to determine the deformation temperature. The results show that conventional compressors are not suitable for high-pressure use, due to the very low COP of the cycle (only 0.5). With a CO₂ compressor, the cycle can achieve a COP of 3.07 at an evaporation temperature of 10 °C. This value is equivalent to the COP of the current commercial air conditioning system. Dang et al. [14] studied a stratified refrigeration system using R134a/CO₂ refrigerant by experimental method. With low-level CO₂ with a condensation temperature of 7.9°C and an evaporation temperature of -30°C, the cooling capacity of the system is 1.62 kW, and the efficiency factor of the system is 1.9. In addition, the theoretical results are well consistent with the experimental results; the error is less than 10%. In addition, Dang et al. [15] experimented on the heat transfer properties of a double-tube heat exchanger in a cascade refrigeration system using the R32/CO₂ pair as the refrigerant. The results obtained from the experimental data are in good agreement with the theoretical calculations. These results are important for calculating and designing a bed heat exchanger using CO₂.

Through the above studies, the thermodynamic parameters for the R513A/R744 cascade refrigeration system are currently quite few and have not been studied much. Therefore, it is important to make reasonable research for this system. In this study, the cooling capacity of the structural system was about 1.5 kW, the evaporation temperature of the R744 medium was -25°C, and the cold room temperature was -20°C.

2.0 METHODOLOGY

2.1 Governing equations

To analyze the thermodynamic parameters of the R513A/R744 cascade refrigeration system and the system coefficient of performance (COP), the governing equations for the low stage cycle and the high stage cycle are given as below:

For the low stage with R744 refrigerant

The heat transfer rate of the evaporator was calculated as:

$$Q_{0(R744)} = m_1 \times (h_1 - h_4) \quad (1)$$

with m_1 is the mass flow rate of the low stage CO₂ and h is enthalpy

The isotropic power input was calculated by:

$$N_{(R744)} = m_1 \times (h_2 - h_1') \quad (2)$$

The heat transfer rate of the cascade heat exchanger (the condenser - evaporator) was calculated as:

$$Q_{K(R744)} = m_1 \times (h_2 - h_3) \quad (3)$$

The COP for the CO₂ cycle was determined by:

$$COP_{R744} = \frac{Q_{0(R744)}}{N_{(R744)}} \quad (4)$$

where N is the isotropic power input and Q is the heat flow rate.

For the high stage with R513A refrigerant

The heat transfer rate of the evaporator was calculated as:

$$Q_{0(R513A)} = Q_{K(R744)} \quad (5)$$

The mass flow rate of the high stage R513A:

$$m_2 = \frac{Q_{0(R513A)}}{h_1 - h_4} \quad (6)$$

The isotropic power input was determined by:

$$N_{(R513A)} = m_2 \times (h_2 - h_1') \quad (7)$$

The heat transfer rate of the R513A condenser was calculated as:

$$Q_{K(R513A)} = m_2 \times (h_2 - h_3') \quad (8)$$

The coefficient of performance of the R134a cycle was quantified by:

$$COP_{R513A} = \frac{Q_{0(R513A)}}{N_{(R513A)}} \quad (9)$$

Finally, the coefficient of performance of the cascade refrigeration system R513A/R744:

$$COP = \frac{Q_{0(R744)}}{N_{(R744)} + N_{(R513A)}} \quad (10)$$

2.2 Experimental set up

The experimental diagram of cascade system for R513A/R744 was shown in Figure 1. In this study, the R513A refrigerant was used for high stage cycle and the R744 refrigerant was used for low stage cycle, it was operated to collect the thermodynamic parameters such as temperature, pressure of both R513A and R744. In this study, the evaporation temperature of R513A is changed from 0.8 to 2°C and the evaporation temperature of R744 is kept at -25°C. The system uses the welding plate heat exchanger (Fig. 2). Also, the time for reaching the temperature of cold storage (at -20°C) is approximately 30 minutes.

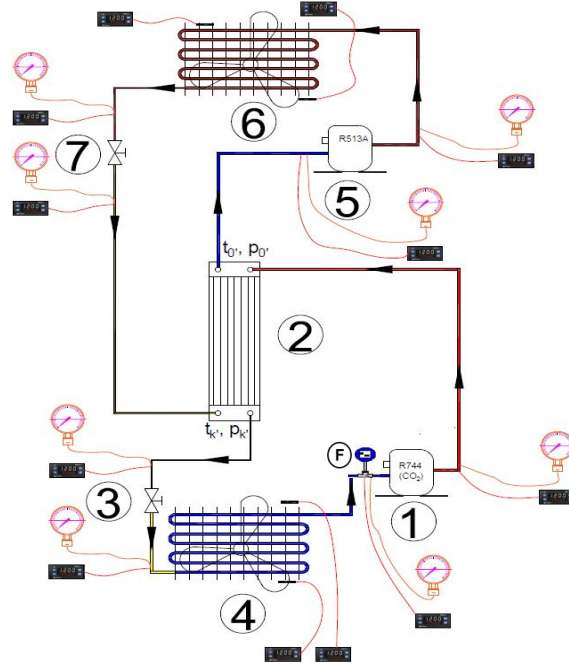


Figure 1. The principal diagram and position of measuring device in the R513A/R744 cascade system

(1 – R744 Compressor, 2 – Cascade heat exchanger (welding plate), 3 – R744 Expansion valve, 4 – R744 Evaporator, 5 – R513A Compressor, 6 – R513A Condenser, 7 – R513A Expansion valve, 8 – Thermal flow meter).



Figure 2. Photos of R513A/R744 cascade system

The accuracy and range of measuring devices are indicated in Table 1. The equipments used for the experiments are listed as follows:

- Thermocouples, T-types
- Thermostat, EW – 181 H, made by Ewelly
- Infrared thermometer, AT 430L2, made by APECH
- Infrared thermometer, Raynger@ST, made by Raytek
- Pressure gauge, made by Pro – Instrument

- Pressure sensor, made by SENSYS, Korea
- Thermal flow meter, made by JUJIE TECH
- Turbine flow meter, made by Digital Flow, Korea.
- Anemometer, AVM-03, made by Prova
- Clamp meter, Kyoritsu 2017, made by Kyoritsu.

Table 1. Accuracies and ranges of testing apparatuses

<i>Measuring device</i>	<i>Accuracy</i>	<i>Range</i>
Thermocouples	$\pm 0.1\text{ }^{\circ}\text{C}$	0 ~100 $^{\circ}\text{C}$
Infrared thermometer	$\pm 1\text{ }^{\circ}\text{C}$ of reading	- 32 ~ 400 $^{\circ}\text{C}$
Pressure gauge	$\pm 1\text{ FS}$	0~100 kgf/cm ²
Pressure sensor	$\pm 0.5\text{ FS}$	0~100 bar
Thermal flow meter	$\pm 1 \sim 2.5\text{ \%}$	0.1 ~ 120 m/s
Turbine flow meter	$\pm 0.5\text{ RS}$	400~5000 l/h
Clamp meter	$\pm 1.5\text{ \% rdg}$	0 ~ 200 A
Anemometer	$\pm 3\text{ \%}$	0 ~ 45 m/s

3.0 RESULTS AND DISCUSSION

The cascade refrigeration system was experimented on more times to collect the stable data under the ambient temperature around 32 $^{\circ}\text{C}$. The volumetric flow rate of the R744 was measured by a thermal flow meter with a value of 270l/h. The results of the R744 test in the low stage cycle are shown in Table 2. A cycle superheat of 18.5 $^{\circ}\text{C}$ can be observed. Based on the experimental data, the R744 cycle is shown in Figure 3 using the EES (Engineering Equation Solver) software.

Table 2. The experimental data of R744 in low stage cycle

Points	t ($^{\circ}\text{C}$)	p (bar)	h (kJ/kg)
1	-26	16.75	437.06
1'	-6.5	16.75	433.89
2	62	36.65	501.65
3	5.8	36.65	215.08
3'	3.4	36.65	208.82
4	-26	16.75	208.82

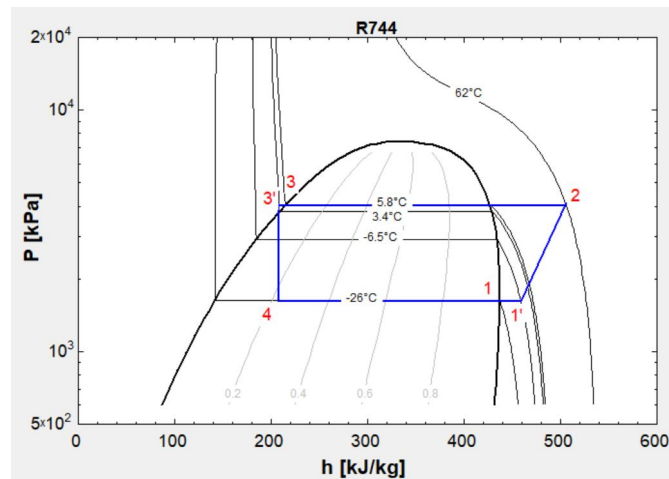


Figure 3. The lg P-h diagram of R744 in low stage cycle

With the high stage cycle of R513A, the experimental results are shown in Table 3 and Figure 4. The temperature difference between the high stage evaporation temperature and the low stage

condensation temperature in a stratified heat exchanger is about 3°C. The experimental results of R513A and R744 indicate that at a saturation pressure, the experimental temperature has a difference with the value obtained from the theoretical temperature; the difference is due to experimental errors. However, the experimental results are in good agreement with the results obtained from the theoretical results, with error less than 10%.

Table 3. The experimental data of R513A in high stage cycle

Points	t (°C)	p (bar)	h (kJ/kg)
1	0.8	2.5	399.19
1'	5	2.5	401.49
2	58.2	9.8	426.07
3	34.7	9.8	247.6
3'	30.6	9.8	241.72
4	3	2.5	241.72

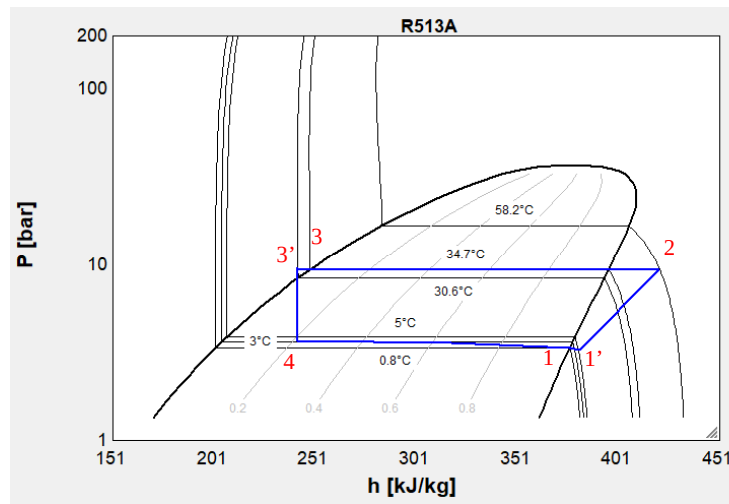


Figure 3. The p-h diagram of R513A in high stage cycle

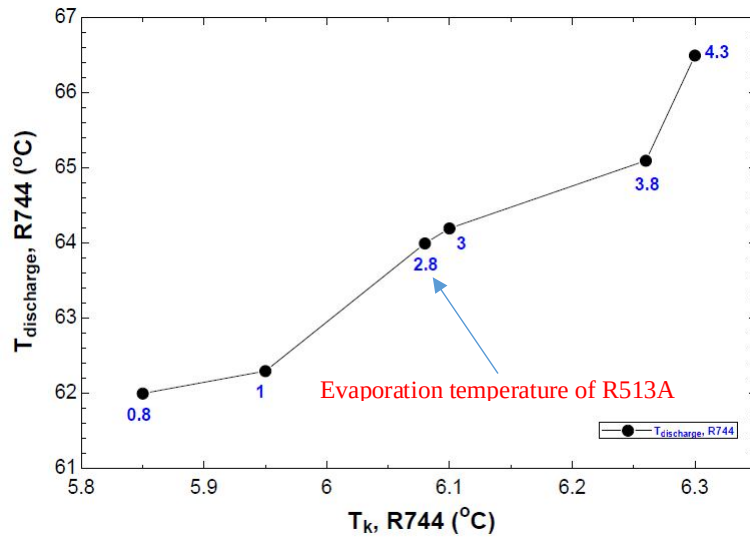


Figure 4. The discharge temperature vs. the condensation temperature of R744

The experimental data was studied on the evaporation temperature of R513A in high stage cycle was changed from 0.8 to 4.3 °C and the constant evaporation temperature of R744 is -25°C in low stage cycle. A relationship between the discharge temperature and the condensation temperature of R744 is shown on Fig. 4. It is observed that the evaporation temperature of R513A affects to the condensation temperature and the discharge temperature of R744. When the evaporation temperature of R513A does down from 4.3 to 0.8 °C, the condensation temperature of R744 reduces from 6.3 to 5.85 °C and the discharge temperature of R744 also reduces from 66.5 to 62 °C.

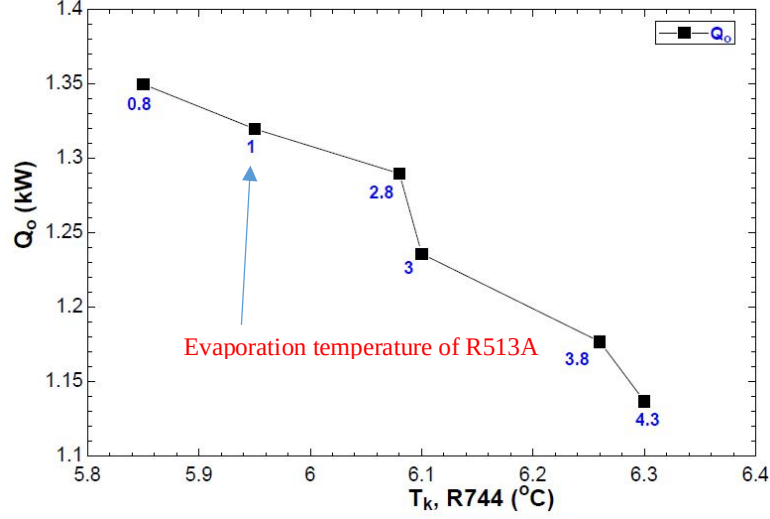


Figure 5. The cooling capacity vs. the condensation temperature of R744

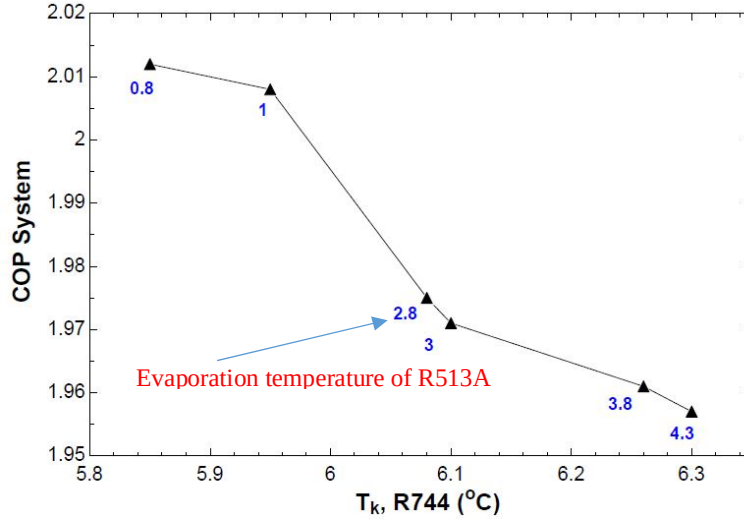


Figure 6. The COP vs. the condensation temperature of R744

Figure 5 indicates a relationship between the cooling capacity and the condensation temperature of R744 in low stage cycle when the evaporation temperature of R513A changes. When the condensation temperature of R744 rises from 5.8 to 6.3 °C, the evaporation temperature of R513A also goes up from 0.8 to 4.3 °C, the cooling capacity goes down from 1.35 to 1.13 kW. Similarly, the COP of cascade system was shown in Fig. 7. When the condensation temperature of R744 increases from 5.8 to 6.3 °C, the COP decreases from 2.01 to 1.96.

4.0 CONCLUSION

This study has experimented with a cascade refrigeration system using R513A/R744 refrigerant pair. R513A refrigerant was used for high stage cycle and R744 refrigerant was used for low stage cycle.

The experimental data were obtained under the same ambient temperature of 32°C. For this study, the cold chamber temperature dropped from 32°C to -20°C over a period of 35 minutes. The thermodynamic parameters of the cascade system have been shown in more detail. R744 at the low stage has a condensation temperature of 5.8°C and an evaporation temperature of -25°C. The cooling capacity of the system is 1.35 kW and the COP of the system is 2.

In addition, the theoretical results are consistent with the experimental results. Results distributed to supplement the experimental data needed when studying stratified refrigeration systems using R744 refrigerant.

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