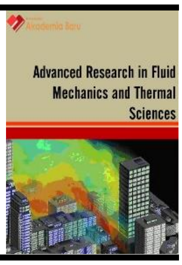
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Energy and Exergy Analysis of Cascade Refrigeration System Using MC22 and MC134 on HTC, R404A and R502 on LTC

Hendri[1,*], Roswati Nurhasanah[1], Prayudi[1], Suhengki[1]

[1] Department of Mechanical Engineering, Fakultas Teknologi dan Bisnis Energi, Institut Teknologi PLN, Jakarta, Indonesia

ARTICLE INFO

Article history:
Received 11 October 2020
Received in revised form 29 December 2020
Accepted 3 January 2021
Available online 2 February 2021

ABSTRACT

Low temperature storage with a single refrigeration system only stable up to 228 K temperature. The purpose of this study is to develop a low temperature cool storage with cascade refrigeration system, with hydrocarbon refrigerants in terms of energy and exergy analysis. Experimental research in laboratories using refrigerant hydrocarbon MC22 and MC134 on the hight temperature circuit, and R404A and R502 using on low temperature circuit. Condenser heat exchanger using a type of exchanger plate. Resulting from this research, obtained that result the MC22/R404A, MC22/R502 and MC134/R404A refrigerant pair can reach a temperature of 220 K. The MC22/R404A refrigerant pair has god performance, COP, total loss exergy, and exergy efficiency is better than MC22/R502, and MC134/R04A refrigerant pairs.

Keywords:
cascade refrigeration system; refrigerant hydrocarbon; COP; total loss exergy; exergy efficiency

1. Introduction

Storage space requirements at low temperature less than -40ºC, in biomedicine, agriculture, and fish products cannot use a single refrigeration system, because a single refrigeration system only stable at minimum temperature of -40ºC [1]. The cascade refrigeration system (CRS), consisting of two system that work independently consisting of a high temperature circuit (HTC), and low temperature circuit (LTC) which is connected the condenser heat exchanger to solve this problem [2]. Global warming issues and restrictions on use CFC and HFC refrigerant, many studies use hydrocarbon refrigerant as its working fluid [3].

Refrigerant as a working fluid can be chosen must have characteristic a large latent heat, pressure must not too high so that the compressor power is low, non-tonic, non-flammable, non-corrosive, environmentally friendly, and low cost [4, 5]. The problem is hydrocarbon refrigerant has flammable [6, 7]. Guidelines that can be used to select the refrigerant pair in the CRS are refrigeration on the HTC should use refrigerant that have high COP, and on the LTC side which has low COP, low pressure

* *Corresponding author.*
E-mail address: hendri@itpln.ac.id

https://doi.org/10.37934/arfmts.80.1.7383

[8]. Refrigerant which is usually used in the HTC is Ammonia (NH3), and in LTC is carbon dioxide, where the cooling in the evaporator between -80ºC to -40ºC in review papers by several authors [9]–[13]. The maximum COP if CRS is influenced by increase in evaporation temperature and decrease in the condenser temperature [14]

In general, same refrigerant use to hight temperature is R22, R32 [15] and refrigerant used for HTC are R152a, R290, R507A, R12, R22, R717, R290, R404, R404A, R717, R744, whit refrigerant for LTC are R23, R744, R170/R744, R290, R170/R744. The parameters observed were COP, cooling capacity, energy, efficiency exergy and thermo economic [16-17]. Research and development CRS for low temperature usually uses carbon dioxide and ammonia (R744) [17]

Refrigerant currently used to achieve low temperature require vacuum pressure and mixture refrigerant, but there are also difficulties [11]. To get low temperature, be required high pressure compressor in each series in the CRS, so that costs will be expensive [18]. Therefore, to develop a low temperature cold storage, then development a low temperature cold storage with CRS and hydrocarbon refrigerant. Refrigerant hydrocarbon used in this research is MC22 (Propane) and MC134 on HTC, and R404A dan R502 on LTC. The parameter observed were temperature evaporation, COP cascade, the effect of decrease temperature cascade, total loss of exergy, mass ratio, and exergy efficiency.

2. Methodology

Model the circuit of CRS the used in this study was developed based on the results of research development by Alhamid [18] as shown in Figure 1.

Based on the p-H diagram in Figure 2, CRS thermodynamic analysis is based on assumptions development by Lui [19], Sarkar [20], and Anand [21] that is :

I. The compression process takes place adiabatic, but not isentropic, isentropic efficiency compressor of 0,75 for both LTC and HTC.
II. The conditioning of the refrigerant out the cascade heat exchanger for the HTC cycle under conditions saturated vapor, and the refrigerant out the cascade heat exchanger for LTC cycle under conditions saturated liquid.
III. Heat transfer in heat exchanger take place is isobaric (constant pressure)
IV. Heat exchanger with the environment is ignored for all component except the condenser
V. Refrigerant expansion in expansion valve isenthalpic
VI. Changes in potential energy and kinetic energy are ignored.

All thermodynamic properties obtained from experimental study results were obtained from software Coolpack_1.5, then the thermodynamic analysis uses the help of Microsoft Excel software. The data needed in thermodynamic analysis is obtained from measuring devices installed at point such as in Figure 1, while the cooling load uses the lamp load at a load of 40 watts. Length of time for observations made in each case is one hour. In various low temperature much research uses the pair R747 and R717, but if using ammonia refrigerant must be replace the pipes in the evaporator and condenser. This is due, usually in the refrigeration system of pipes that are used using copper pipe material because it has a large heat transfer coefficient. While the copper pipe will react with ammonia. Therefore, the refrigerant pair used in the research is the refrigerant pairs used are Musicool MC22 (propane), MC134 on HTC, and R404A, R502 on LTC.

Thermodynamic analysis used in the CRS is energy balance approach [22], and exergy analysis approach [23, 24] as shown in Table 1.

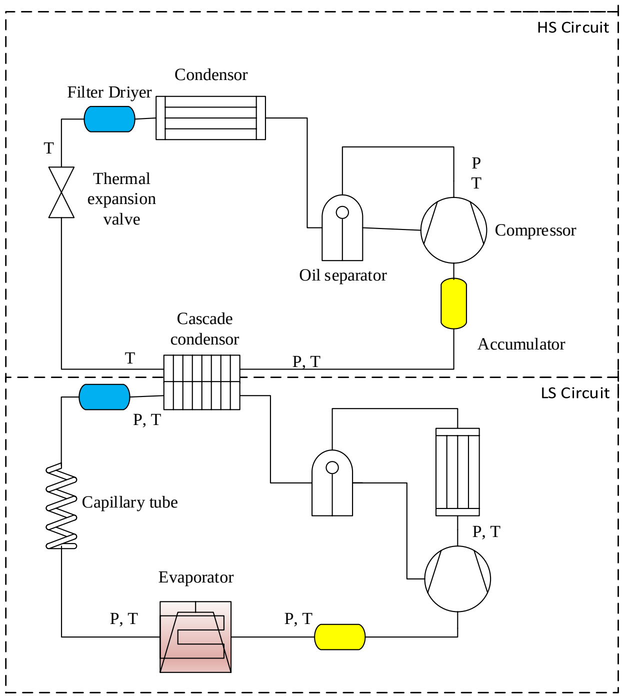


Fig. 1. Cascade refrigeration system

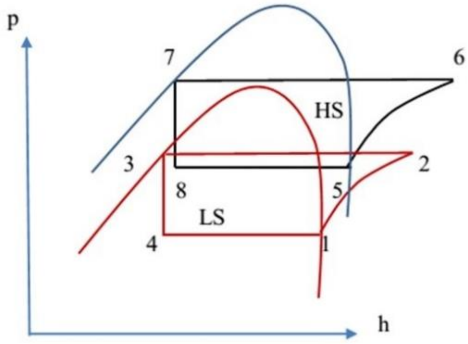


Fig. 2. p-h diagram for CRS

Table 1
Heat balance equation for each component [14, 23-24]

component	Mass balance	Exergy balance	Exergy balance
HTC			
Compressor	$m_5 = m_6 = m_H$	$W_H = \frac{m_H}{\eta}(h_6 - h_5)$	$X_{CmH} = m_H T_o(s_6 - s_5)$
Condenser	$m_6 = m_7 = m_H$	$Q_H = m_H(h_6 - h_7)$	$X_{CnH} = Q_H - m_H T_o(s_6 - s_7)$
Expansion device	$m_7 = m_8 = m_H$	$h_7 = h_8$	$X_{EDH} = m_H T_o(s_7 - s_8)$
Cascade heat exchanger	$m_8 = m_5 = m_H$ $m_3 = m_2 = m_H$	$Q_{cas} = m_H(h_5 - h_8)$ $Q_{cas} = m_L(h_2 - h_3)$	$X_{CHE} = T_o\{m_H(s_7 - s_8) + m_L(s_2 - s_3)\}$
LTC			
Compressor	$m_1 = m_2 = m_L$	$W_L = \frac{m_L}{\eta}(h_2 - h_1)$	$X_{CmL} = m_L T_o(s_2 - s_1)$
Condenser	$m_2 = m_3 = m_L$	$Q_L = m_L(h_2 - h_3)$	$X_{CnL} = Q_L - m_L T_o(s_2 - s_3)$
Expansion device	$m_3 = m_4 = m_L$	$h_3 = h_4$	$X_{EDL} = m_L T_o(s_3 - s_4)$
Evaporator	$m_4 = m_1 = m_L$	$Q_L = m_L(h_1 - h_4)$	$X_E = T_o\left[m_L(s_1 - s_4) - \frac{Q_L}{Te + \Delta T}\right]$

In the mathematical model heat transfer equations in the table above, soma studies assume isentropic efficiency compressor η=0,70 [10], η=0,874-0,0135.Rp [14], η=1-0,04RC [22], and η=1,0 [24]. In this study it is assumed, the isentropic efficiency compressor is η=0,85. If power on compressor LTC is P_1 watt, the amount of mass on LTC m_1 can be calculated from the energy balance [22].

$$P_L = \frac{m_L}{\eta_C}(h_2 - h_1) \quad (1)$$

Form heat and mass balance on CRS, ratio mass defined by,

$$Q_{cas} = m_H(h_5 - h_8) = m_L(h_2 - h_3), \quad (2)$$

$$\frac{m_H}{m_L} = \frac{h_2 - h_3}{h_5 - h_8} \quad (3)$$

Coefficient of performance (COP) form CRS defined by [22]

$$COP_{cas} = \frac{Q_L}{W_H + W_L} \quad (4)$$

Total energy loss system is the sum of all exergy of each component. So the total exergy loss CRS is calculated by defined [14],

$$X_{total} = \sum X_i \quad (5)$$

While the efficiency exergy CRS is defines as the ratio of the minimum work required to all total actual work that is [14],

$$\eta_{CRS} = \frac{W_H + W_L - X_{total}}{W_H + W_L} \quad (6)$$

3. Results and Analysis

3.1 Effect of Evaporator and Condenser Temperatures on CRS Performance

The effect of evaporation and condenser temperatures on CRS performance in terms of COP, total loss exergy Eq. (3), exergy efficiency Eq. (5) and mass ratio Eq. (3), given by the following Figure 3 to 8.

3.1.1 Effect evaporator temperature on COP cascade

The effect of evaporator temperature on the COP cascade which will be discussed is given in Figure 3, the following.

Based on Figure 3, evaporator temperature that can be achieved 220 K, if the evaporator temperature raises, the COP rises. This condition is caused by the higher temperature of the evaporator or lower temperature evaporation, pressure in the evaporator gets lower to vacuum. The impact on the temperature very low requires W_L a high compressor pressure on LTC [9]. The impact if the temperature in evaporator rises the compressor work on LTC lower, the consequence COP cascade will rise. This statement is relevant to the research [14,23-25], From Figure 1, maximum COP MC22-R404A is 1,01. CRS with refrigerant pair MC22/R404A have better COPs than refrigerant pairs MC22-R502 and MC134-R404A.

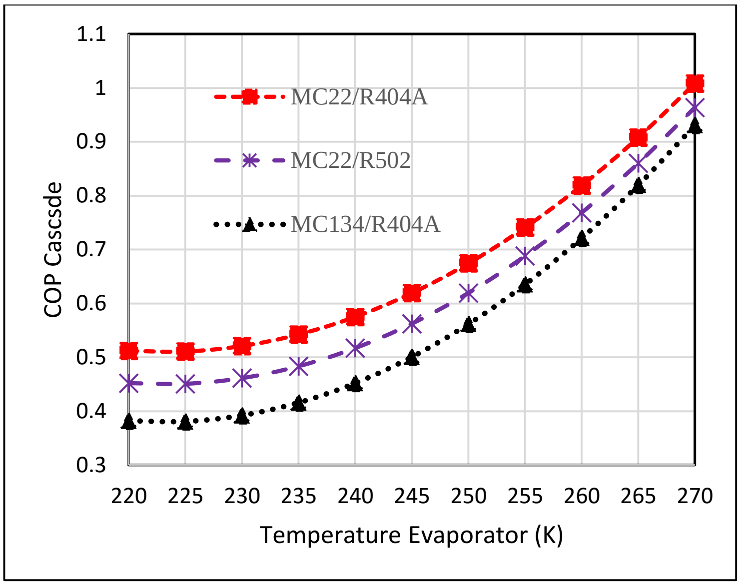


Fig. 3. Effect temperature evaporator on COP cascade

3.1.2 Effect temperature condenser on COP cascade

Figure 4 below shows the effect of condenser temperature on COP at condenser temperature from 300 K to 330 K. The temperature of the condenser is measured from the condenser exit temperature on the HTC.

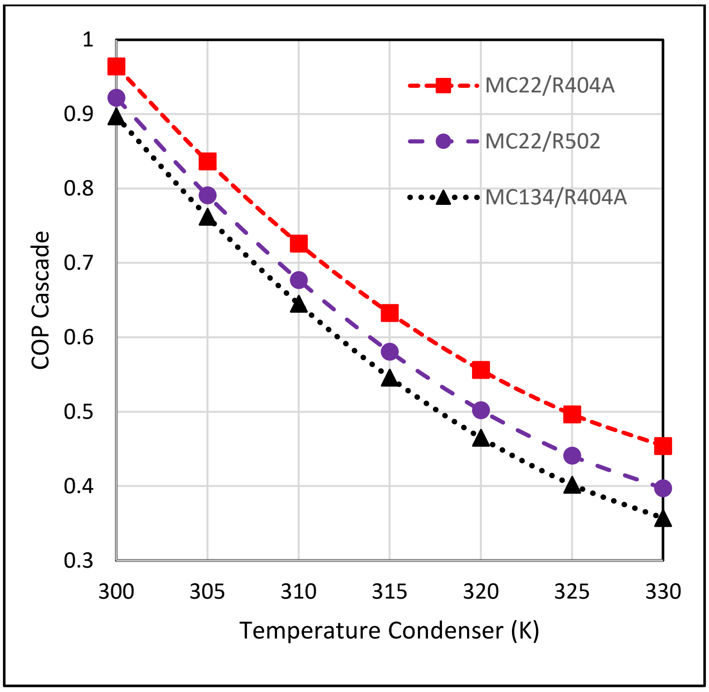


Fig. 4. Effect temperature condenser on COP cascade

Based on Figure 4, if the temperature condenser HTC rise from 300 K to 330 K, the COP cascade will go down. The phenomenon, if the condenser temperature rises or temperature out compressor HTC rises, if takes a large compressor work HTC, the impact of COP cascade will be decreases. The lowest cascade COP of 0,35 is indicated by MC134-R404A. The condition of COP cascade reduction is relevant to the results of study [22, 23, 26] if the HTC condenser temperature rises, the COP cascade drops. The relationship between COP and condenser temperature is not linier.

3.1.3 Effect temperature evaporator and condenser on exergy

Figure 5 Show that the effect of evaporator temperature on total exergy loss, which show the relationship of energy loss is needed if the evaporator temperature reaches 220 K. Evaporator temperature observed at 220 K to 270 K. The relationship between evaporator temperature and total exergy loss is not linier.

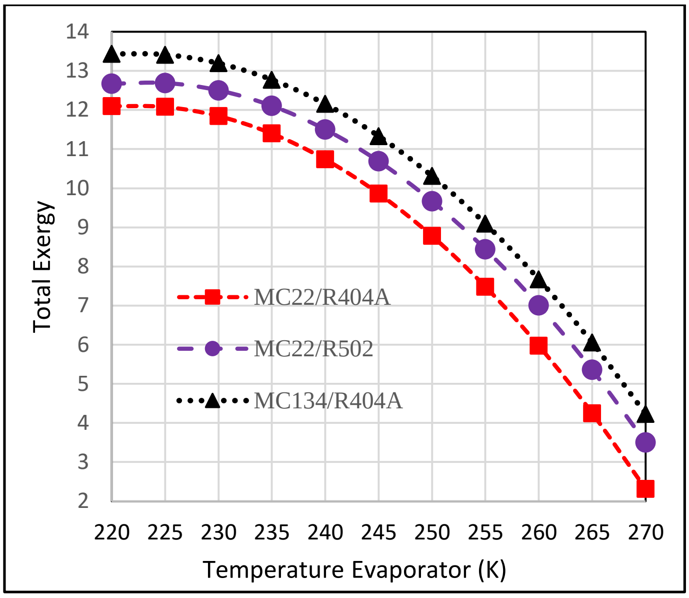


Fig. 5. Effect of evaporator temperature on total exergy loss

From Figure 5, it shows if the evaporator temperature goes up increase from 200 K to 270 K, the total exergy loss or total energy loss decreases. While the lowest amount of energy loss is MC22-R404A, the highest total exergy loss is MC134-R404A which is 11.75 kW, when evaporator temperature 220 K. The results of this phenomenon are relevant to results research [19, 21-22].

Figure 6, it shows that effect evaporator temperature on exergy efficiency, where the relationship is not linier. If the LTC evaporator temperature increase, the exergy efficiency will increase and will drop again. This mean that the greatest loss of exergy ratio if evaporator temperature between 220 K to 270 K. The lowest exergy efficiency at MC134/R404A is around 0,2743 or 27,43 %. The highest exergy efficiency at MC22/R404A is around 0,521 or 52,1 %. This is in accordance with the conditions in Figure 5, if the total heat loss is large, then the exergy efficiency will decrease. The results of this phenomenon are relevant to results research review papers by several author [20-22] that is if the evaporator temperature increase, the exergy efficiency will increase, and the relationship is not linier.

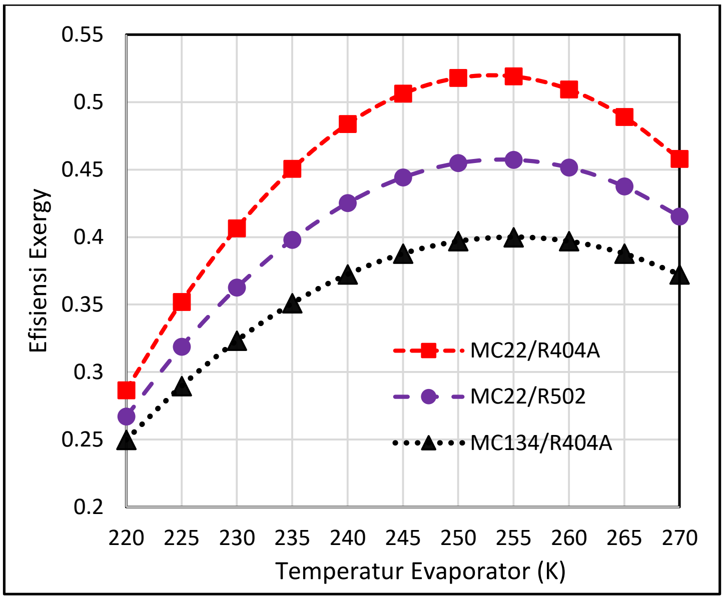


Fig. 6. Effect of evaporator temperature on efficiency exergy

The opposite of Figure 6, in Figure 7 shows that if condenser temperature increase, the exergy efficiency will decrease. The condenser temperature observed at a 300 K to 330 K. The exergy efficiency decreases because if the evaporator temperature rises, and total exergy also rises, the impact exergy efficiency will decrease. The MC22/R404A refrigerant pair has an exergy efficiency greater than other refrigerant pairs. The relationship between condenser temperature and exergy efficiency is not linier, will reach a minimum value under certain conditions. The results of this research are relevant to the results of study can be seen in review papers by several authors [19, 20, 22], that is, if the condenser temperature rises, the exergy efficiency will decrease.

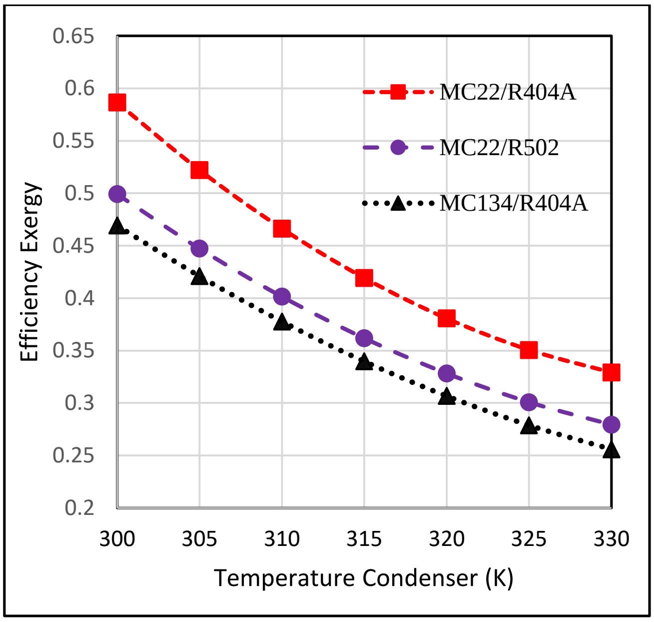


Fig. 7. Effect of condenser temperature on exergy efficiency

In Figure 8, shows the effect of evaporator temperature on mass ratio HTC and LTC, where m_H/m_L has a linier trend that is inversely related to increase of evaporator temperature, the mass ratio

m_H/m_L decrease. At a temperature 200 K, mass ratio m_H/m_L MC22-R404A is higher than the others, meaning that to reach this temperature required an amount of R404A refrigerant is greater than MC22. On the other hand, COP cascade and evaporator temperature have non-linier relationship. This indicated that the COP cascade is related to mass ratio m_H/m_Loptimum. The lowest mass ratio is MC134-R404A compared to MC22-R404A and MC22/R502. This result is relevant to study review papers [8, 20]

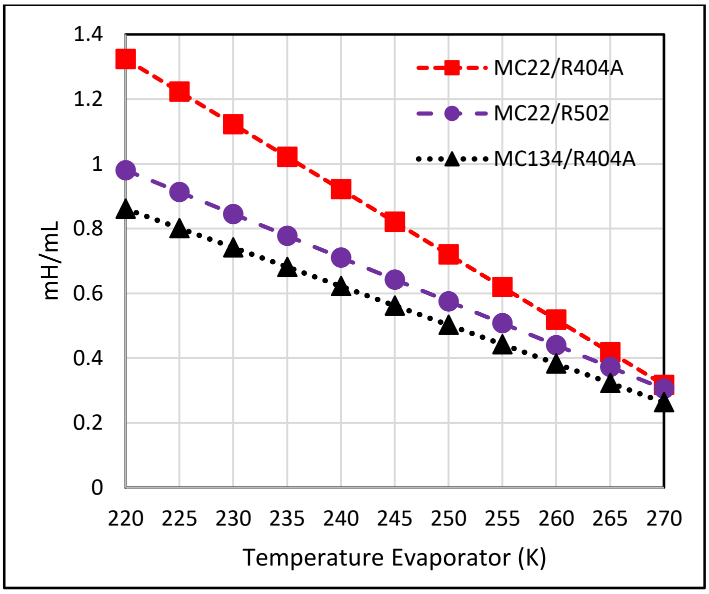


Fig. 8. Effect of evaporator temperature on mass ratio

3.2 Effect ΔT cascade On COP and Exergy Efficiency

In refrigeration systems, exergy analysis is not only used for cascade systems. This method is also used for the air heater system and liquid suction heat exchanger [15-27]. In this case, in several previous studies the performance the cascade heat exchanger was reviewed from the effect of cascade temperature on COP and exergy efficiency, where in principle ΔT cascade is the difference between the temperature in the heat exchanger between the LTC and HTC temperature, which is measured form $\Delta T = T_8 - T_3 = T_5 - T_2$. ΔT observed at 0°C to 30°C.

In Figure 9, shows that effect ΔTcascade on COP cascade at temperature 0°C to 30°C, under operating conditions the evaporator temperature is 220 K to 270 K. From Figure 9. If ΔTcascade increase, then the COP cascade will go down. The lowest COP cascade is MC134/R404A, and COP cascade MC22-R404A is greater than MC22-R502 and MC134/R404A. Relationship of COP cascade and ΔT cascade is not linier. COP cascade maximum if ΔT = 0. The phenomenon of decrease COP cascade due to the decrease ΔT cascade this is identical to the increase condenser temperature, this meaning that increase ΔT cascade resulting in increased the compressor work. These results are identical to the results of the research can be seen in review papers by several authors [22, 24-26].

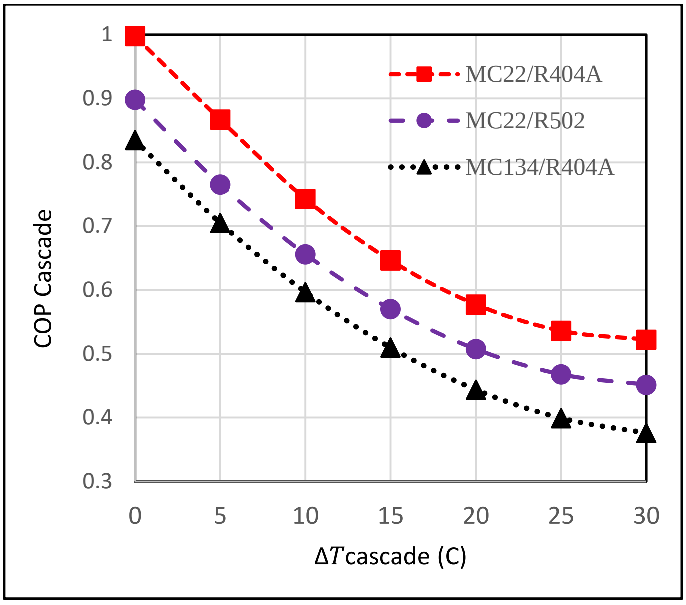


Fig. 9. Effect ΔTcascade on COP cascade

In Figure 10, shows that effect ΔT cascade temperature on exergy efficiency, where if ΔTcascade increase than exergy efficiency decrease. The lowest exergy efficiency is on MC134/R404A, which mean that it is increasing ΔT cascade temperature and exergy efficiency will decrease, meaning that using MC134/R404A refrigerant required large energy or high compressor work. This low exergy efficiency is due to large total exergy loss, due to the difference in LTC and HTC temperature in large heat exchanger. This can be interpreted that the greater temperature difference between LTC and HTC in heat exchanger, the HTC and LTC compressor work will be even greater, and the amount of heat expended by evaporator into the environment is also large.

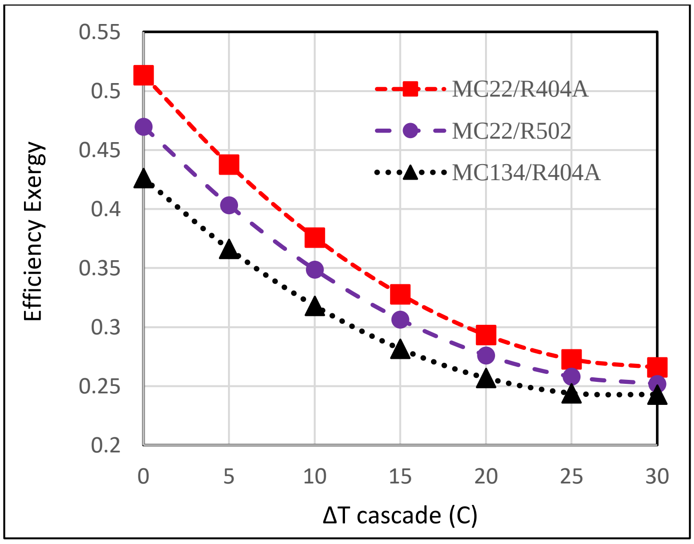


Fig. 10. Effect ΔTcascade *on* exergy efficiency

4. Conclusion

In this research, a low temperature refrigeration storage system with a cascade refrigeration system was developed using a pair of refrigerants from MC22/R404A, MC22/R502 or MC134/R404A. From the results of the above analysis it can be concluded that the MC22/R404A refrigerant has better performance, COP, and exergy efficiency compared to MC22/R502 or MC134/R404A. Hydrocarbon refrigerant MC22 used in the cascade refrigeration system still needs to be continued, it is recommended for use on HTC on CRS, and R404A refrigerant for LTC on CRS. From the experimental results, it was found that the evaporator temperature of the refrigerant pair reached 220 K, the development of the cascade refrigeration system still needs to be continued, to get an even lower storage temperature

Acknowledgement
This research was supported by the Department's Excellent Internal Research Grant 2019/2020, Institut Teknologi PLN, Jakarta.

Reference

[1] Syaka, Darwin RB, and Muhammad Idrus Alhamid. "A Cascade refrigeration system using mixture of carbon dioxide and hydrocarbons for low temperature applications." *Journal of Engineering and Applied Sciences* 6, no. 6 (2011): 379-386.

[2] Ashrae, ASHRAE Handbook. "Refrigeration (SI Edition)." *American Society of Heating, Refrigerating & Air-Conditioning Engineers, Atlanta* (2014).

[3] Aziz, Azridjal, and Afdhal Kurniawan Mainil Thalal. "Effect of Cooling Load on the Performance of R22 Residential Split Air Conditioner when Retrofitted with Hydrocarbon Refrigerant (HCR22)." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 48, no. 1 (2017): 100-108. https://doi.org/10.1088/1757-899X/237/1/012010

[4] Morad, Akeel Mohammed Ali. "A Two-Phase Pressure Drop Model for Homogenous Separated Flow for Circular Tube Condenser, Examined with Four Modern Refrigerants." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 52, no. 2 (2018): 274-287.

[5] Prayudi and R. Nurhasanah. "Analysis of effect of sub cooling performance of vapour compression refrigeration system with cooling load variation." *ARPN J. Eng. Appl. Sci.*, 11, no. 2 (2016): 906–911.

[6] Alhamid, M. Idrus, Nasruddin, Arnas Lubis, Kiyoshi Saito, Hajime Yabase, and Nyayu Aisyah. "Energy Analysis for the Solar Thermal Cooling System in Universitas Indonesia." *International Journal of Air-Conditioning and Refrigeration* 27, no. 03 (2019): 1950023. https://doi.org/10.1142/S2010132519500238

[7] Syaka, Darwin RB, I. Wayan Sugita, and Muhammad Bijaksana. "CHARACTERISTICS STUDY OF TWO-STAGE CASCADE REFRIGERATION SYSTEM DESIGN FOR HOUSEHOLD AIR BLAST FREEZING." *Int. J. Mech. Eng. Technol.*, 10, no. 1 (2019): 1804–1813.

[8] Pan, Mingzhang, Huan Zhao, Dongwu Liang, Yan Zhu, Youcai Liang, and Guangrui Bao. "A Review of the Cascade Refrigeration System." *Energies* 13, no. 9 (2020): 2254. https://doi.org/10.3390/en13092254

[9] Dalkilic, Ahmet Selim. "Theoretical analysis on the prediction of performance coefficient of two-stage cascade refrigeration system using various alternative refrigerants." *1st Bilimi ve Tekniği Dergisi, J. of thermal science and technology* 32, no. 1 (2012).

[10] Messineo, Antonio. "R744-R717 cascade refrigeration system: performance evaluation compared with a HFC two-stage system." *Energy Procedia* 14 (2012): 56-65. https://doi.org/10.1016/j.egypro.2011.12.896

[11] P. Vyas, S. Ghodke, and A. Wamankar. "Optimization of Natural Refrigerants Carbon Dioxide (R744) and Amoonia (R717) in Cascade Refrigeration System Using Genetic Algorithm." *J. Information, Knowl. Res. Mech. Eng.*, 01, no. 02 (2016): 73–79.

[12] Ma, Ming, Jianlin Yu, and Xiao Wang. "Performance evaluation and optimal configuration analysis of a CO2/NH3 cascade refrigeration system with falling film evaporator–condenser." *Energy conversion and management* 79 (2014): 224-231. https://doi.org/10.1016/j.enconman.2013.12.021

[13] Tripathy, Satyananda, Jibanananda Jena, Dillip K. Padhiary, and Manmatha K. Roul. "Thermodynamic analysis of a cascade refrigeration system based on carbon dioxide and ammonia." *J. Eng. Res. Appl.* 4, no. 1 (2014): 2248–962224.

[14] Sun, Zhili, Qifan Wang, Zhiyuan Xie, Shengchun Liu, Dandan Su, and Qi Cui. "Energy and exergy analysis of low GWP refrigerants in cascade refrigeration system." *Energy* 170 (2019): 1170-1180.

https://doi.org/10.1016/j.energy.2018.12.055
[15] Tritjahjono, Rachmad Imbang, Kasni Sumeru, Andriyanto Setyawan, and Mohamad Firdaus Sukri. "Evaluation of Subcooling with Liquid-Suction Heat Exchanger on the Performance of Air Conditioning System Using R22/R410A/R290/R32 as Refrigerants." *Journal of Advanced Research in Fluid Mechanics and Thermal Scie*nces 55, no. 1 (2019): 1-11.
[16] Bansal, Pradeep. "A review–Status of CO2 as a low temperature refrigerant: Fundamentals and R&D opportunities." *Applied Thermal Engineering* 41 (2012): 18-29. https://doi.org/10.1016/j.applthermaleng.2011.12.006
[17] Nasruddin, Nasruddin, Arnas Arnas, Ahmad Faqih, and Niccolo Giannetti. "Thermoeconomic optimization of cascade refrigeration system using mixed carbon dioxide and hydrocarbons at low temperature circuit." *Makara Journal of Technology* 20, no. 3 (2016): 132-138. https://doi.org/10.7454/mst.v20i3.3068
[18] Alhamid, M. Idrus, Darwin RBS Nasruddin, and Arnas Lubis. "Characteristics and COP Cascade Refrigeration System using Hydrocarbon Refrigerant (Propane, Ethane and CO2) at Low Temperature Circuit (LTC)." *International Journal of Technology* 4, no. 2 (2013): 112-120. https://doi.org/10.14716/ijtech.v4i2.125
[19] Zhang, Li, Shiming Xu, Ping Du, and Huanying Liu. "Experimental and theoretical investigation on the performance of CO2/propane auto-cascade refrigerator with a fractionation heat exchanger." *Applied Thermal Engineering* 87 (2015): 669-677. https://doi.org/10.1016/j.applthermaleng.2015.05.016
[20] Sarkar, Jahar, Souvik Bhattacharyya, and Arjun Lal. "Selection of suitable natural refrigerants pairs for cascade refrigeration system." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 227, no. 5 (2013): 612-622. https://doi.org/10.1177/0957650913487730
[21] Anand, S., A. Gupta, and S. K. Tyagi. "Simulation studies of refrigeration cycles: A review." *Renewable and Sustainable Energy Reviews* 17 (2013): 260-277. https://doi.org/10.1016/j.rser.2012.09.021
[22] Yilmaz, Baris. "Thermodynamic analysis and optimization of cascade condensing temperature of a CO2 (R744)/R404A cascade refrigeration system." *Int. Refrig. Air Cond. Conf.* 2 (2014): 1–10.
[23] Alhamid, M. Idrus, and Darwin RB Syaka. "Exergy and energy analysis of a cascade refrigeration system using R744+ R170 for low temperature applications." *Int. J. Mech. Mech. Eng.*, 10, no. 6 (2010): 1–8.
[24] Ust, Yasin, and A. Sinan Karakurt. "Analysis of a Cascade Refrigeration System (CRS) by Using Different Refrigerant Couples Based on the Exergetic Performance Coefficient (EPC) Criterion." *Arabian Journal for Science and Engineering* 39, no. 11 (2014): 8147-8156. https://doi.org/10.1007/s13369-014-1335-9
[25] Sun, Zhili, Youcai Liang, Shengchun Liu, Weichuan Ji, Runqing Zang, Rongzhen Liang, and Zhikai Guo. "Comparative analysis of thermodynamic performance of a cascade refrigeration system for refrigerant couples R41/R404A and R23/R404A." *Applied Energy* 184 (2016): 19-25. https://doi.org/10.1016/j.apenergy.2016.10.014
[26] Saengsikhiao, Piyanut, Juntakan Taweekun, Kittinan Maliwan, Somchai Sae-ung, and Thanansak Theppaya. "Development of Environmentally-Friendly and Energy Efficient Refrigerant for Medium Temperature Refrigeration Systems." *Journal of Advanced Research in Materials Science* 71, no. 1 (2020): 12-31. https://doi.org/10.37934/arms.71.1.1231
[27] Ghaderian, J., C. N. Azwadi, and H. Mohammed. "Modelling of energy and exergy analysis for a double-pass solar air heater system." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 16, no. 1 (2015): 15-32.