

Thermodynamic Performance Study of Cascade Cooling Systems on Cruise Ships with Mixed Working Fluids and Operating Parameters

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Abstract

The cooling system is an important component on cruise ships to maintain engine operating temperatures and operational reliability. However, conventional cooling systems still have limitations in terms of energy efficiency and high thermodynamic losses. This study aims to analyze the performance of cascade cooling systems on cruise ships with variations in mixed working fluids, temperatures, pressures, and mass flow rates. The analysis was conducted using an energy and exergy approach to evaluate the Coefficient of Performance (COP), exergy efficiency, and exergy destruction. The study was conducted on a modified two-stage cascade cooling system. The working fluids analyzed include R22/R404A, R290/R404A, and R290/R600a. The results show that a decrease in mass flow rate in the high-temperature cycle increases the COP value, while an increase in temperature in Heat Exchanger Y increases exergy efficiency. The R22/R404A combination produced the highest exergy efficiency, while the hydrocarbon-based combination showed potential for COP improvement. This study demonstrates that optimizing operating parameters and selecting the appropriate working fluid can improve the energy efficiency of cascade refrigeration systems on cruise ships.

Keywords: cascade cooling system; cruise ship; mixed working fluid; coefficient of performance (COP); exergy efficiency

Abstrak

Sistem pendingin merupakan komponen penting pada kapal pesiar untuk menjaga temperatur kerja mesin dan keandalan operasional. Namun, sistem pendingin konvensional masih memiliki keterbatasan dalam efisiensi energi dan tingginya kerugian termodinamika. Penelitian ini bertujuan menganalisis kinerja sistem pendingin cascade pada kapal pesiar dengan variasi fluida kerja campuran, temperatur, tekanan, dan laju aliran massa. Analisis dilakukan menggunakan pendekatan energi dan eksergi untuk mengevaluasi Coefficient of Performance (COP), efisiensi eksergi, dan exergy destruction. Kajian dilakukan pada sistem pendingin cascade dua tahap yang dimodifikasi. Fluida kerja yang dianalisis meliputi R22/R404A, R290/R404A, dan R290/R600a. Hasil penelitian menunjukkan bahwa penurunan laju aliran massa pada siklus temperatur tinggi meningkatkan nilai COP, sedangkan peningkatan temperatur pada Heat Exchanger Y meningkatkan efisiensi eksergi. Kombinasi R22/R404A menghasilkan efisiensi eksergi tertinggi, sementara kombinasi berbasis hidrokarbon menunjukkan potensi peningkatan COP. Penelitian ini menunjukkan bahwa optimasi parameter operasi dan pemilihan fluida kerja yang tepat dapat meningkatkan efisiensi energi sistem pendingin cascade pada kapal pesiar.

Kata kunci: sistem pendingin cascade; kapal pesiar; fluida kerja campuran; coefficient of performance (COP); efisiensi eksergi

1. Introduction

Energy conservation in the maritime sector has become a global focus to reduce fuel consumption and greenhouse gas emissions, as stipulated in MARPOL Annex VI. Since 2011, the IMO has established ship energy efficiency regulations in line with greenhouse gas emission control [1]. However, the energy efficiency of ship cooling systems is still relatively low, even though these systems play an important role in maintaining engine performance and ship operational reliability. Failures in the cooling system can cause serious disruptions to overall ship operations [2]. Therefore, optimizing the cooling system is a strategic step in creating more environmentally friendly ships with the potential to save up to 25% in electricity and around 1,5% in fuel.

In ship cooling systems, the Coefficient of Performance (COP) and exergy efficiency are important parameters for improving operational performance and reducing environmental impact. Exergy analysis can identify the location, type,

and level of energy loss so that resource utilization efficiency can be improved [3][4]. Research by Shestopalov et al., [5] indicates that ejector compression combination systems have a COP that is 13,5-15,6% higher than conventional steam compression systems and are capable of utilizing low-temperature waste heat (85-95°C) to save fuel by 25-33% per voyage. Another study revealed that the main irreversibility in ship cooling systems generally occurs in heat exchangers, pumps, and condensers due to entropy generation and exergy destruction [3]. Ineffective cooling systems can cause overheating of the main engine and increase the risk of damage, so good temperature control is important to extend engine life and reduce maintenance costs [6]. In absorption cooling systems, exergy efficiency is greatly influenced by operating conditions and energy system integration. Samiee and Aghdam [7], reported the highest exergy efficiency of 40.13% in summer and the lowest of 9.3% in winter on cruise ships, while Que et al. [8] showed that integrating absorption cooling systems with SOFC and gas turbines can achieve exergy efficiency of up to 68,45%, offering great potential for energy savings and emission reductions in the marine sector.

Various studies show that exergy efficiency plays an important role in improving ship cooling system performance and reducing environmental impact. A study by Asal, Acir and Dincer [9] on integrated cruise ship multigeneration systems reported an exergy efficiency of 15,35%, but the maximum exergy efficiency was still very low (0,0039%). Meanwhile, Patiluna et al., [10] succeeded in increasing exergy efficiency to 0,32% through system modifications and the use of refrigerant mixtures. However, this exergy efficiency achievement is still limited, indicating a significant research gap for the development of strategies and system configurations that can significantly improve the exergy efficiency of ship cooling systems more optimally.

Ship cooling systems, particularly on cruise ships, play a critical role in maintaining stable engine operating temperatures and preventing overheating that may lead to component degradation or failure. Efficient cooling system performance not only ensures operational reliability but also contributes to improved overall system efficiency and reduced long-term maintenance requirements. This is supported by previous studies, including the authors' earlier work [11], which demonstrated that the performance of cascade refrigeration systems has a significant influence on energy consumption and overall system efficiency. In the previous study, the thermo-environmental performance of cascade refrigeration systems was evaluated using indicators such as the Ecological Coefficient of Performance (ECOP) and Total Equivalent Warming Impact (TEWI), with a primary focus on environmental impact assessment. However, the influence of key operational parameters, particularly mass flow rate and thermodynamic characteristics related to the Coefficient of Performance (COP) and exergy destruction has not yet been comprehensively investigated. Therefore, this study aims to analyze cascade cooling systems by considering variations in mixed working fluids, operating temperatures, pressures, and mass flow rates, in order to evaluate their effects on thermodynamic performance. The findings are expected to contribute to the optimization of system efficiency and to provide a more in-depth understanding of the operational behavior of cascade refrigeration systems.

2. Material and Method

2.1. Material

This study examines a two-stage cascade vapor compression refrigeration system applied to the Vision of the Seas cruise ship. The selection of this ship refers to previous research by Asal, Acir, and Dincer [9], so that ship data and operating conditions are used as the basis for determining the cooling load and system parameters.

The cooling system consists of two main cycles, namely the High Temperature Cycle (HTC) and the Low Temperature Cycle (LTC), which are thermally connected through a cascade condenser. The system includes two compressors, a condenser, an evaporator, a cascade condenser, three expansion valves, two flash chambers, and four internal heat

exchangers (HEw, HEx, HEy, and HEz), as shown in Figure 1. The system is modeled under steady-state conditions, where the compressors are assumed to operate with constant isentropic efficiency, the expansion valves follow an isenthalpic process, and pressure drops in heat exchangers are neglected.

The system is analyzed under fixed operating conditions of 313 K condensation temperature, 233 K evaporation temperature, and 298 K ambient temperature. Variations are applied to the heat exchanger temperatures, with subcooling temperatures ranging between 273–285 K and superheating/desuperheating temperatures between 273–279 K. The mass flow rate in the HTC is varied at 0.65–1.30 kg/s, while the LTC is kept constant. The working fluid combinations considered are R22/R404A, R290/R404A, and R290/R600A.

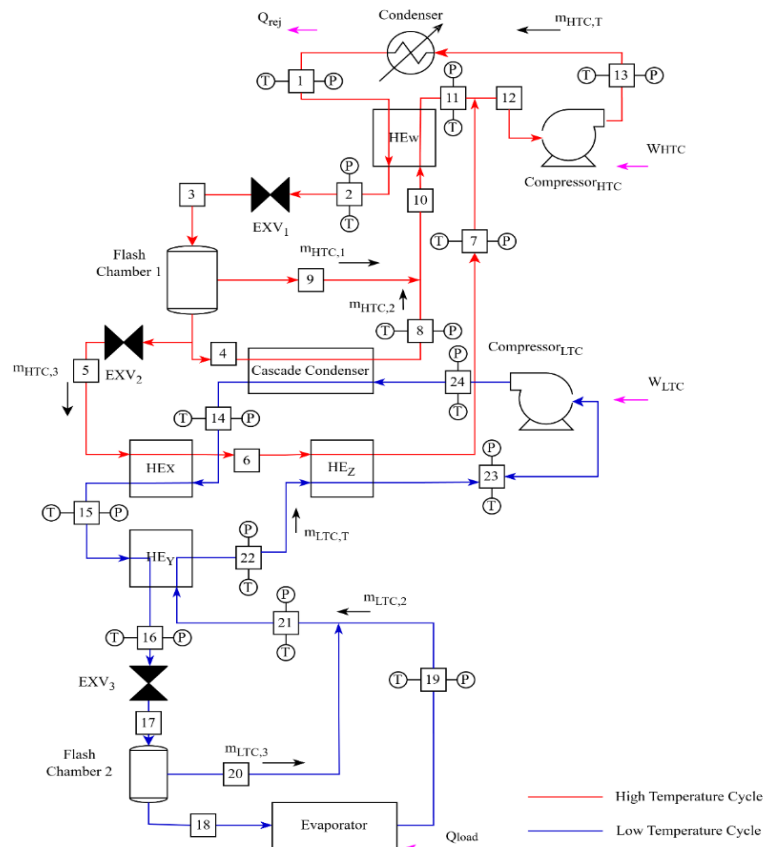


Figure 1. Machine Schematic

2.2. Method

This research method uses numerical simulation combined with energy and exergy analysis. The research began with problem formulation and literature study, followed by data collection and design of a cascade cooling system scheme. A thermodynamic model of the system was developed and simulated using Engineering Equation Solver (EES) software by applying mass, energy, and exergy balance equations to each system component until the validation criteria were met. Next, system performance analysis was conducted using the Coefficient of Performance (COP) parameter, total exergy efficiency, and exergy destruction rate in each component. The simulation was conducted by considering operating parameters such as the type of working fluid, operating temperature in the heat exchanger in the range of 273–283 K, condensation and evaporation pressures, and mass flow rates. The mass flow rate in the high temperature cycle (HTC) was varied by 0,65; 0,91; and 1,30 kg/s, while the mass flow rate in the low temperature cycle (LTC) was kept constant at 0,45 kg/s.

2.3. Thermodynamic Model

The thermodynamic analysis of the cascade cooling system in this study is based on the application of the first and second laws of thermodynamics. The equations used include mass, energy, and exergy balances in each main component of the system to calculate the heat transfer rate, compressor work, Coefficient of Performance (COP), exergy efficiency, and exergy destruction rate. The formulation of equations and analytical approaches used in this study refer to the methods previously applied in research by Patiluna et al. [10].

$$\sum m_{in} = \sum m_{out} \quad (1)$$

The equation represents mass conservation, where the total inlet mass flow rate equals the total outlet mass flow rate. The mass flow rate (m) is expressed in kg/s, and \sum denotes the summation of all inlet and outlet flows.

$$Q - W = \sum m_{out} h_{out} - \sum m_{in} h_{in} \quad (2)$$

This expression represents the steady-flow energy balance for an open system. Q (kW) is the heat transfer rate, W (kW) is the work, and h (kJ/kg) is the specific enthalpy, with *in* and *out* indicating inlet and outlet conditions.

$$E\dot{x}_{des} = \sum_{out} \left(1 - \frac{T_0}{T}\right) \cdot Q - W + \sum_{in} m \cdot (h - T_0 \cdot s) + \sum_{out} m \cdot (h - T_0 \cdot s) \quad (3)$$

$E\dot{x}_{des}$ (kW) denotes the exergy destruction rate, Q (kW) the heat transfer, W (kW) the work, and m (kg/s) the mass flow rate. h and s represent specific enthalpy and entropy, while T_0 and T denote ambient and system temperatures. Subscripts *in* and *out* indicate inlet and outlet conditions.

$$E\dot{x}_{cooling} = \left(\frac{T_0 - T_{evap}}{T_{evap}}\right) Q_{load} \quad (4)$$

This expression is used to calculate the exergy destruction rate during the cooling process in a thermodynamic system. In this context, T_0 represents the ambient (dead state) temperature, while T_{evap} is the evaporation temperature at the evaporator. Q_{load} denotes the cooling load provided by the system. The term $\left(\frac{T_0 - T_{evap}}{T_{evap}}\right)$ reflects the temperature difference between the system and the environment, which influences the magnitude of exergy loss.

$$E\dot{x}_{in} = \dot{W}_{net} = \dot{W}_{LTC} + \dot{W}_{HTC} \quad (5)$$

This expression relates the exergy input rate, $E\dot{x}_{in}$, to the total net power, \dot{W}_{net} , comprising the contributions from the LTC and HTC cycles, denoted as \dot{W}_{LTC} and \dot{W}_{HTC} , respectively.

$$\eta_{II} = \frac{E\dot{x}_{cooling}}{E\dot{x}_{in}} \quad (6)$$

This expression defines the exergy efficiency of the cooling system. $E\dot{x}_{cooling}$ represents exergy loss, while $E\dot{x}_{in}$ is the exergy input. The efficiency η_{II} measures how effectively the system converts input exergy into cooling output

$$COP = \frac{Q_{ref}}{\dot{W}_{LTC} + \dot{W}_{HTC}} \quad (7)$$

This expression defines the Coefficient of Performance (COP), where Q_{ref} is the cooling capacity and $\dot{W}_{LTC} + \dot{W}_{HTC}$ is the total work input. The COP represents the system's efficiency in producing cooling from the supplied work.

3. Results and Discussion

3.1. Coefficient of Performance (COP)

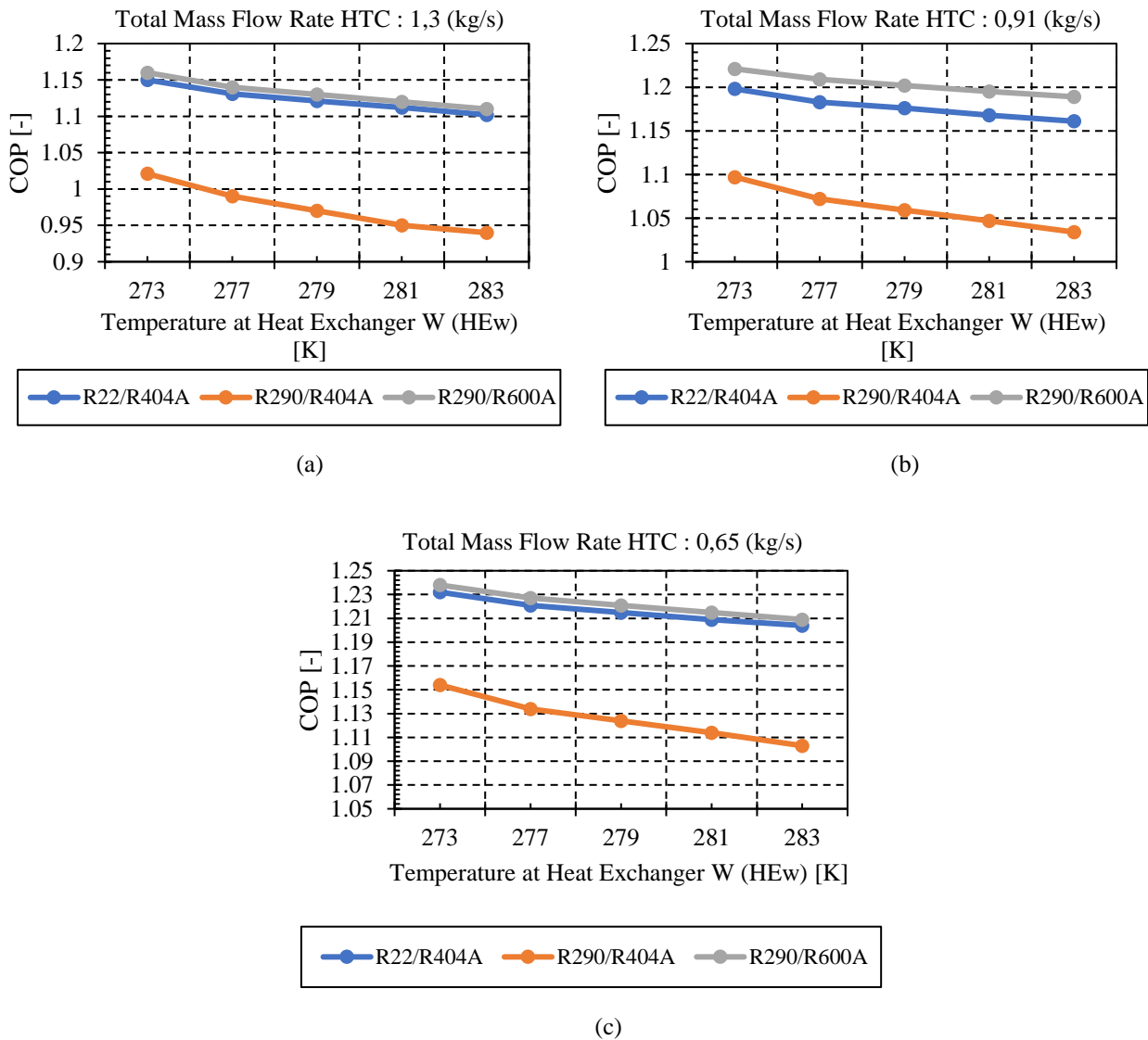


Figure 2. Effect of HEW temperature on the Coefficient of Performance (COP) at varying working fluids for HTC mass flow rates: (a) 1,3 kg/s, (b) 0,91 kg/s, and (c) 0,65 kg/s.

Based on the graphs in Figures 2, a decrease in mass flow rate from 1,30 to 0,65 kg/s generally increases the Coefficient of Performance (COP) value for all refrigerant pairs and HEW temperature variations (273–283 K). At the highest mass flow rate, the COP tends to be lower, especially at high HEW temperatures, due to an increase in compressor workload without a corresponding increase in heat transfer capacity. Conversely, at medium to low mass flow rates, the COP increases and is more stable due to a better balance between heat transfer in the heat exchanger and compressor work. This trend is in line with the findings of Lohar and Mittal [12], who reported an inverse relationship between mass flow rate and COP in vapor compression refrigeration systems. Thermodynamically, a high mass flow rate increases the working pressure and compression ratio, thereby increasing compressor work and decreasing COP, as also reported by Ji and Wang [13]. At lower mass flow rates, the residence time of the refrigerant in the heat exchanger becomes longer, increasing heat transfer efficiency without a significant increase in compressor work. Additionally, an increase in HEW

temperature causes a decrease in COP due to a reduction in the driving force for heat transfer and an increase in compressor load, in accordance with the basic characteristics of the vapor compression cycle and the research results of Faruque et al. [14].

Of all the refrigerant combinations analyzed, the R290/R600A pair consistently produced the highest COP values across all variations in mass flow rate and HEw temperature. This advantage is due to the thermodynamic characteristics of hydrocarbon refrigerants, which have high latent heat, lower compression pressure ratios, and better heat transfer properties, thereby reducing compressor work and increasing system efficiency. These results are in line with the findings of Ozsipahi et al. [15], who reported an increase in COP and a decrease in compressor pressure ratio when using an R290/R600A mixture. In contrast, refrigerant pairs involving R404A showed lower COP values due to higher operating pressures and compression ratios, which increased compressor energy consumption. This is supported by a study by Biçen and Arabacı [16], which indicates that systems with R290 produce higher COP, lower power consumption, and smaller compressor exergy losses compared to R404A. These findings confirm that hydrocarbon refrigerants, particularly R290/R600A, are more thermodynamically advantageous and have the potential to be a more efficient and sustainable alternative.

3.2. Exergy Efficiency

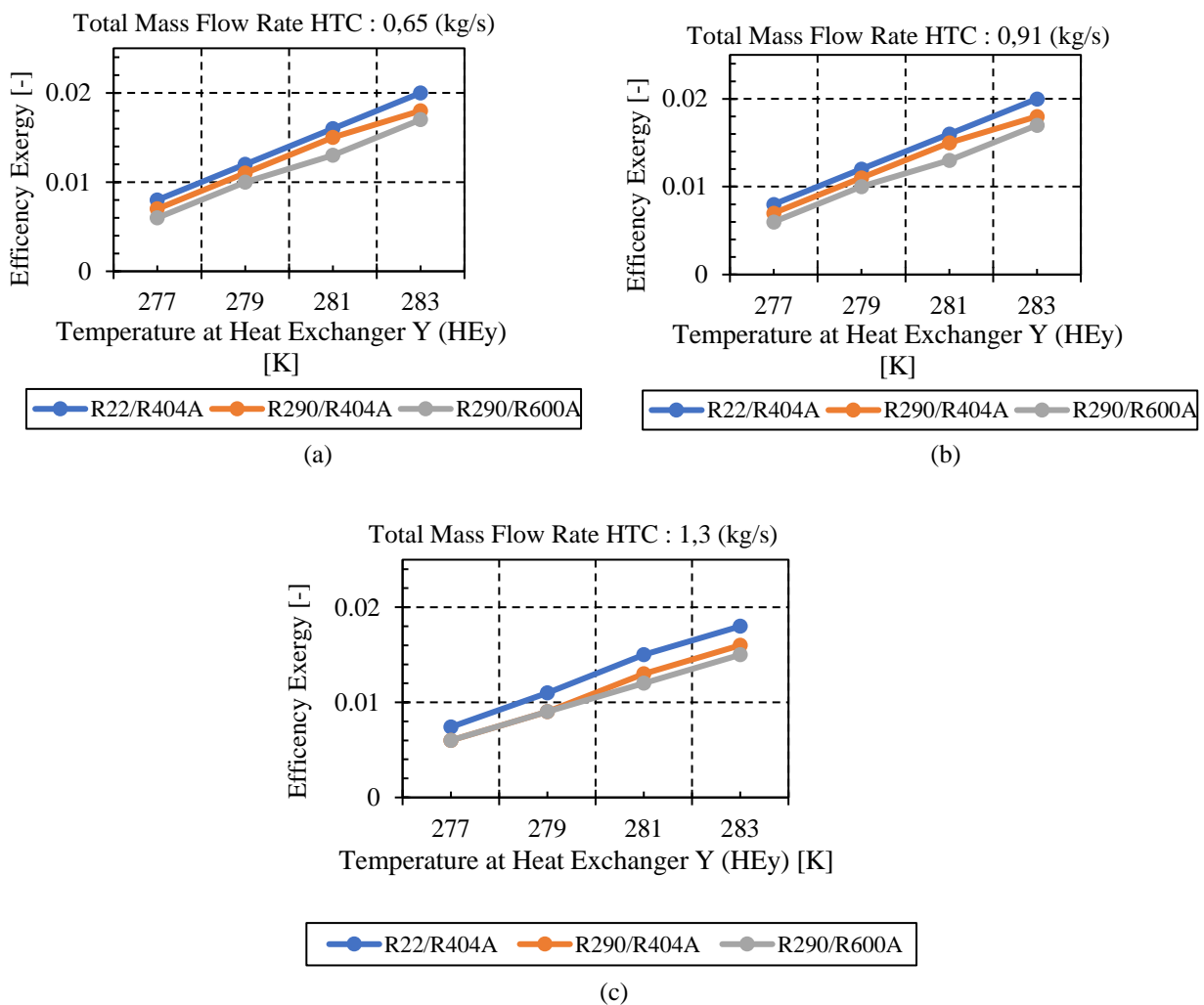


Figure 3. Effect of Heat Exchanger Y (HEy) temperature on exergy efficiency at HTC mass flow rates: (a) 0,65 kg/s, (b) 0,91 kg/s, and (c) 1,3 kg/s.

Based on the analysis results, the temperature at Heat Exchanger Y (HEy) has a significant effect on the exergy efficiency of the cascade cooling system. At all variations of the total mass flow rate of the High Temperature Cycle (HTC), an increase in HEy temperature from 277 K to 283 K consistently increases the exergy efficiency of the system. This is due to the decrease in the temperature difference between the working fluid and the heat transfer medium, thereby reducing the irreversibility of heat transfer and exergy loss. This finding is in line with the research by Scholar et al. [17], which states that the evaporator temperature, condenser temperature, and temperature difference in the cascade heat exchanger are the main parameters that affect the exergy efficiency and Coefficient of Performance (COP) of cascade cooling systems.

The effect of the total HTC mass flow rate on exergy efficiency shows an increasing trend as the mass flow rate increases, especially at higher HEy temperatures. An increase in mass flow rate improves heat transfer effectiveness and reduces thermal irreversibility, but is also accompanied by an increase in compressor work and pressure loss. As a result, the increase in exergy efficiency is not linear and shows the existence of optimal conditions. This phenomenon is consistent with the research results of Deymi-dashtebayaz, Maddah, and Fallahi [18], who reported that the COP and exergy efficiency of the system reached maximum values at the optimum injection mass flow rate, while compressor work and exergy destruction reached minimum values.

In terms of refrigerant combinations, the R22/R404A pair generally produces the highest exergy efficiency compared to R290/R404A and R290/R600A. This is due to the compatibility of the thermophysical properties of the two refrigerants, which result in a lower compression ratio and more uniform temperature distribution, thereby reducing system irreversibility. Conversely, hydrocarbon-based refrigerant combinations tend to have greater differences in pressure and temperature characteristics, thereby increasing irreversibility in the compressor and heat exchanger. These results are in line with the research by Shanmugasundar et al. [19], which indicates that differences in the thermophysical properties of refrigerants have a direct effect on COP and exergy efficiency, even though hydrocarbon refrigerants still have advantages in terms of environmental sustainability due to their lower global warming potential (GWP) and zero ozone depletion potential (ODP).

3.3. Exergy Destruction Rate

Based on the graph in Figure 4, an increase in the temperature of Heat Exchanger W (HEw) from 273 K to 283 K consistently increases the exergy destruction rate in the cascade cooling system for all variations in the total mass flow rate of the High Temperature Cycle (HTC) and refrigerant combinations. This trend indicates that an increase in HEw temperature increases the irreversibility of the system due to an increase in the thermodynamic imbalance between the working fluid and the environment, thereby increasing the potential for work loss during the heat transfer process. These results are in line with Jeon's research [20], which reports that internal heat exchangers contribute significantly to the irreversibility of cascade refrigeration systems, although under certain conditions they can increase exergy efficiency. In terms of the effect of the total HTC mass flow rate, an increase in the mass flow rate from 0,65 kg/s to 1,3 kg/s causes an increase in the exergy destruction rate across the entire HEw temperature range. This is due to the increase in energy and exergy flowing into the system, which increases irreversibility due to flow friction, pressure drop, and increased compressor work. This finding is consistent with the exergy analysis results conducted by Chaturvedi, Sharma, and Ranganayakulu [21], which show that an increase in mass flow rate and compressor work is directly correlated with an increase in irreversibility and a decrease in system exergy efficiency.

Based on the refrigerant combination, the R290/R600A pair showed the highest exergy destruction rate under all operating conditions, indicating a greater degree of irreversibility due to the differences in the thermophysical

characteristics of the two refrigerants. Conversely, the R22/R404A combination produced the lowest exergy destruction rate, indicating the suitability of the thermodynamic properties of the two refrigerants so that the process was closer to reversible conditions. These findings are in line with the study by Almeida and Almeida [22], which reported that in addition to the compressor, the heat exchanger component, particularly the cascade condenser, which is the main contributor to irreversibility, and the differences in the thermophysical properties of refrigerants greatly affect the energy and exergy performance of cascade refrigeration systems.

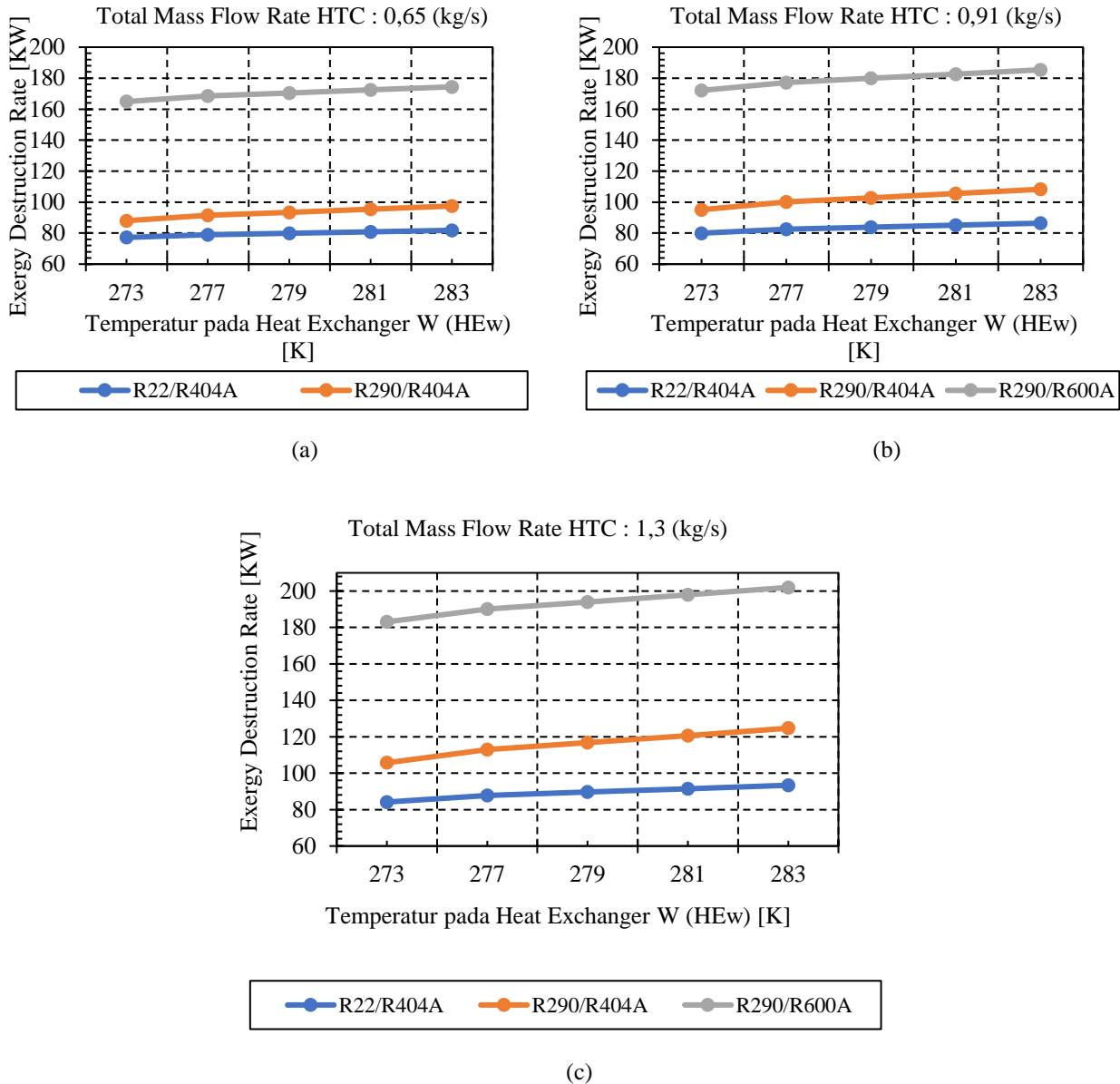


Figure 4. Effect of HEw temperature on the exergy destruction rate at varying working fluids for HTC mass flow rates: (a) 0,65 kg/s, (b) 0,91 kg/s, and (c) 1,3 kg/s.

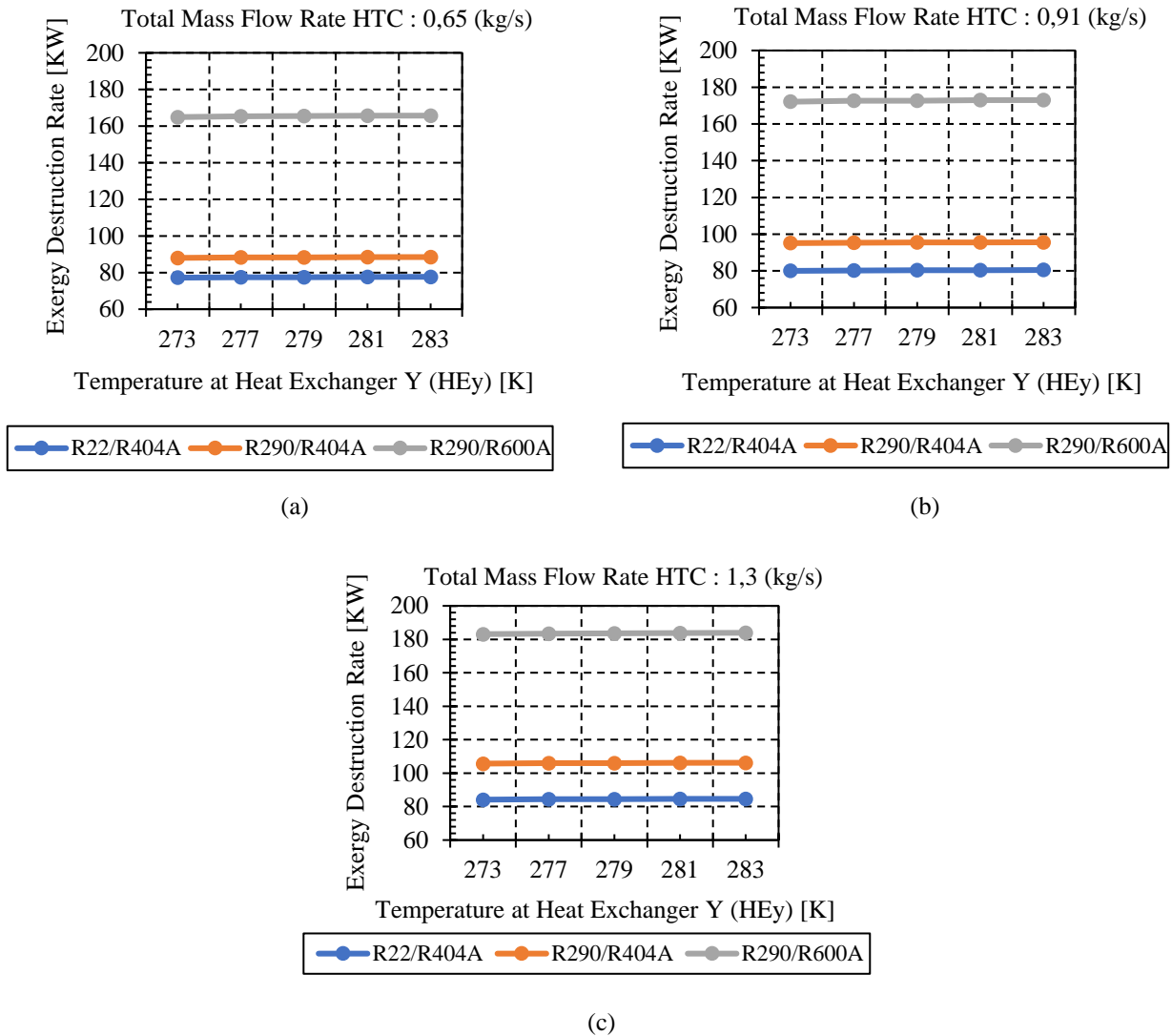


Figure 5. Effect of HEy temperature on the exergy destruction rate for variations in working fluid for HTC mass flow rates: (a) 0,65 kg/s, (b) 0,91 kg/s, and (c) 1,3 kg/s.

Based on the graph of the relationship between the exergy destruction rate and the temperature of Heat Exchanger Y (HEy), changes in HEy temperature from 273 K to 283 K do not have a significant effect on the exergy destruction rate value across all variations in the total mass flow rate of the High Temperature Cycle (HTC) and refrigerant combinations. The exergy destruction rate value tends to be relatively constant with very small fluctuations, indicating that the heat transfer process in HEy is stable and that narrow temperature variations are not sufficient to increase the irreversibility of the system. These results are in line with the findings of Voloshchuk et al. [23] who stated that in certain heat exchangers, the effect of small temperature variations on exergy destruction is relatively smaller than the effect of flow parameters. Conversely, increasing the total mass flow rate of the HTC from 0,65 kg/s to 1,3 kg/s consistently increases the exergy destruction rate due to increased energy and exergy flow, flow friction, pressure drop, and compressor work requirements. In terms of refrigerant combinations, the R290/R600A pair showed the highest exergy destruction rate, followed by R290/R404A, while R22/R404A produced the lowest value. This confirms that differences in the thermophysical properties of refrigerants, such as working pressure, compression ratio, and heat transfer characteristics, play a dominant role in determining the level of system irreversibility. Overall, these results are consistent with Voloshchuk et al. [23],

who concluded that exergy destruction in heat exchangers is more sensitive to mass flow rate and refrigerant selection than to relatively small temperature variations.

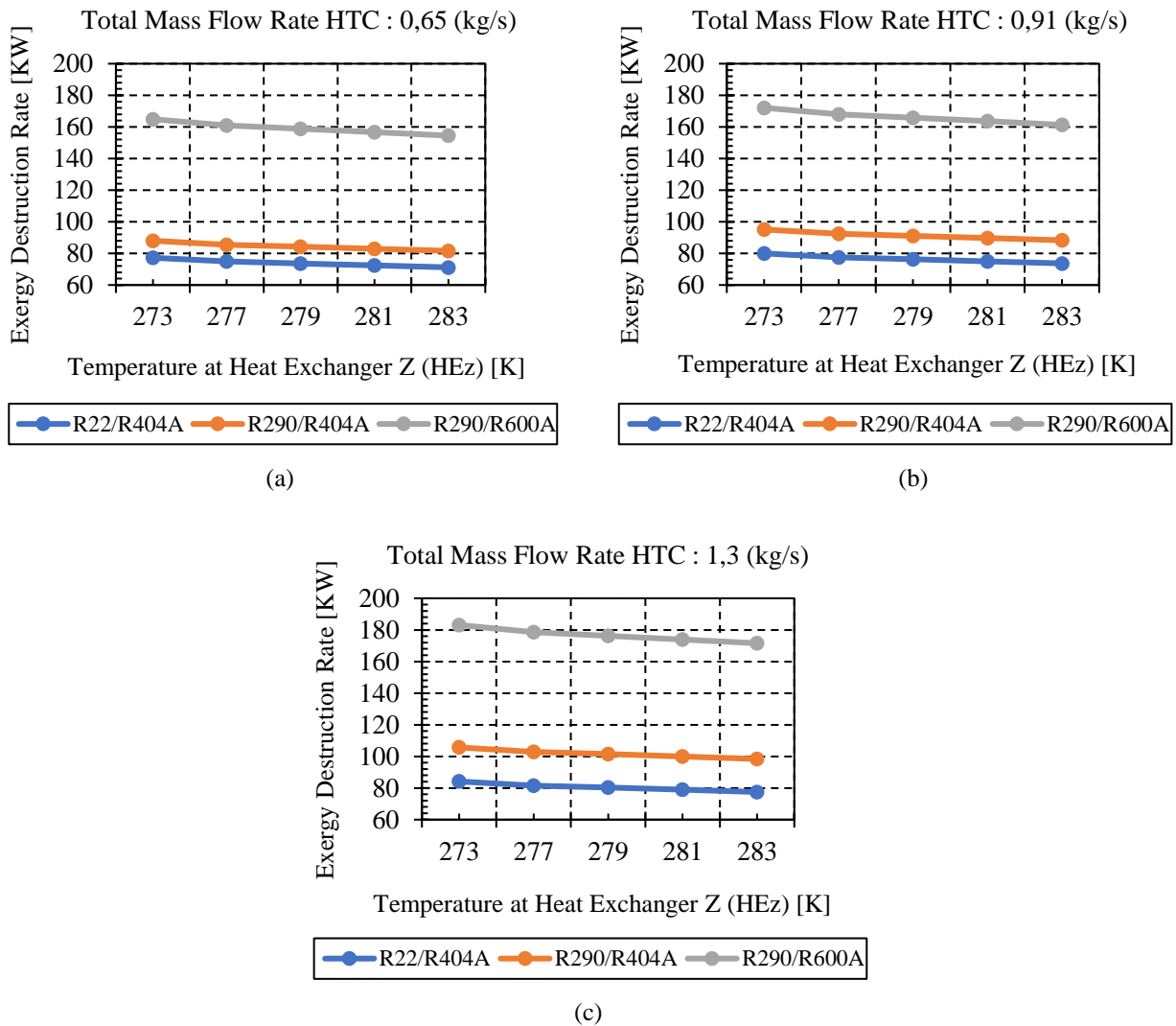


Figure 6. Effect of HEz temperature on the exergy destruction rate for variations in working fluid for HTC mass flow rates: (a) 0,65 kg/s, (b) 0,91 kg/s, and (c) 1,3 kg/s.

Based on the graphs in Figures 6, an increase in Heat Exchanger Z (HEz) temperature from 273 K to 283 K causes a decrease in the exergy destruction rate across all variations in the total mass flow rate of the High Temperature Cycle (HTC) and refrigerant combinations. This trend indicates that an increase in HEz temperature reduces thermal irreversibility due to a decrease in the temperature difference (temperature driving force, ΔT) between the working fluid and the heat transfer medium, thereby minimizing exergy loss, as reported by Voloshchuk et al. [23] regarding the effect of pinch point temperature difference on irreversibility in condensers and evaporators. Conversely, increasing the total HTC mass flow rate from 0,65 kg/s to 1,3 kg/s generally increases the exergy destruction rate due to increased energy and exergy flow, flow friction, pressure drop, and increased compressor work. In terms of refrigerant combinations, the R290/R600A pair showed the highest exergy destruction rate, followed by R290/R404A, while R22/R404A produced the lowest value, confirming that differences in the thermophysical properties of refrigerants play an important role in determining the level of system irreversibility and that optimizing the mass flow rate and selecting refrigerants are key to reducing avoidable exergy destruction.

4. Conclusion

Based on the results of thermodynamic analysis of cascade cooling systems on cruise ships with variations in working fluid, temperature, pressure, and mass flow rate, it can be concluded that system performance is greatly influenced by the combination of these operating parameters. Decreasing the mass flow rate of the High Temperature Cycle (HTC) from 1,30 kg/s to 0,65 kg/s generally increases the Coefficient of Performance (COP) due to reduced compressor work, although an excessively low mass flow rate has the potential to reduce cooling capacity. An increase in the temperature of Heat Exchanger Y (HEy) has been shown to improve the exergy efficiency of the system due to a decrease in thermal irreversibility, while an analysis of the exergy destruction rate indicates that an increase in temperature at Heat Exchanger W (HEw) increases irreversibility, while at Heat Exchanger Z (HEz) it actually decreases it. In terms of working fluid combinations, the R22/R404A pair produced the highest exergy efficiency and lowest exergy destruction rate, while hydrocarbon-based combinations showed higher irreversibility under certain conditions despite being more environmentally friendly. Overall, the results of this study indicate that cascade cooling systems have great potential to improve energy efficiency and operational sustainability of cruise ships through optimization of working fluid selection, heat exchanger temperature control, and determination of optimal mass flow rates.

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References

- [1] A. Komara, J. S. Saragih, K. Rasyad, K. T. P. Iroth, M. Dwiwanti, and S. U. Sahubawa, "Strategi Membangun Ekonomi Sirkular Industri Maritim Nasional melalui Konsep Net Zero Emission," *Maj. Tek. Ind.*, vol. 31, no. 1, pp. 1–10, 2023, doi: 10.61844/majalahteknikindustri.v31i1.665.
- [2] S. Klara, "Analisis Keandalan Sistem Pendingin Mesin Induk Kapal KM. Pangrango," *J. Ris. Teknol. Perkapalan*, vol. 1, no. 1, pp. 8–13, 2023.
- [3] M. S. Holle and R. Roekmono, "Analisis Eksergi dan Optimisasi Termoekonomi pada Sistem Refrigerasi di Data Center Menggunakan Metode Algoritma Genetika," *J. Tek. ITS*, vol. 9, no. 2, 2021, doi: 10.12962/j23373539.v9i2.58538.
- [4] A. A. Aloanis, H. Taunaumang, A. Rampengan, and J. Polii, "Analisis Eksergi Dan Optimasi Pembangkit Listrik Tenaga Panas Bumi Lahendong Unit-2," *J. FisTa Fis. dan Ter.*, vol. 2, no. 2, pp. 66–75, 2021, doi: 10.53682/fista.v2i2.131.
- [5] K. Shestopalov *et al.*, "Novel marine ejector-compression waste heat-driven refrigeration system : Technical possibilities and environmental advantages," *Int. J. Refrig.*, vol. 158, no. November 2023, pp. 202–215, 2024, doi: 10.1016/j.ijrefrig.2023.11.015.
- [6] A. A. Pratama, N. Astriawati, P. S. Waluyo, and R. Wahyudiyana, "Optimalisasi Perawatan Sistem Pendingin Mesin Utama Di Kapal MV. Nusantara Pelangi 101," *Maj. Ilm. Bahari Jogja*, vol. 20, no. 1, pp. 1–11, 2022, doi: 10.33489/mibj.v20i1.289.
- [7] S. Samiee and A. H. Aghdam, "4E analysis of a solar , wind and waste heat-driven CCHP system : A case study for a cruise ship Organic Rankine cycle," *Appl. Therm. Eng.*, vol. 252, no. May, p. 123600, 2024, doi: 10.1016/j.applthermaleng.2024.123600.

- [8] W. Que *et al.*, “Potential of solid oxide fuel cells as marine engine assisted by combined cooling and power cogeneration systems,” *Applied Thermal Engineering*. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2024.123821>
- [9] S. Asal, A. Acir, and I. Dincer, “A sustainable cruise ship development with cleaner production of electricity, heat, cooling, freshwater and hydrogen,” *J. Clean. Prod.*, vol. 467, no. May, p. 142939, 2024, doi: 10.1016/j.jclepro.2024.142939.
- [10] D. Nygeil *et al.*, “Energy and exergy analysis of a two-stage cascade vapor compression refrigeration system with modified system configuration Coefficient of Performance,” vol. 169, no. August 2024, pp. 33–54, 2025, doi: 10.1016/j.ijrefrig.2024.10.013.
- [11] D. Natasya and F. A. Rayhan, “Thermo-Environmental Performance Analysis of Cascade Refrigeration System on Cruise Ship Applications,” vol. 11, no. 1, pp. 282–292, 2026.
- [12] Y. Lohar and R. Mittal, “Experimental Performance Analysis and Evaluation of COP of Vapor Compression Refrigeration System on Different Mass Flow Rate of R134a as Refrigerant,” vol. 5, no. 12, pp. 269–273, 2019.
- [13] Z. Ji and H. Wang, “Gas-Liquid Flow of R290 in the Integrated Electronic Expansion Valve and Vapor Injection Loop for Heat Pump,” pp. 1–25, 2025.
- [14] W. Faruque, M. R. Uddin, S. Salehin, and M. M. Ehsan, “A Comprehensive Thermodynamic Assessment of Cascade Refrigeration System Utilizing Low GWP Hydrocarbon Refrigerants,” *Int. J. Thermofluids*, vol. 15, no. July 2022, p. 100177, 2027, doi: 10.1016/j.ijft.2022.100177.
- [15] M. Ozsipahi, H. A. Kose, H. Kerpicci, and H. Gunes, “Experimental study of R290 / R600a mixtures in vapor compression refrigeration system,” *Int. J. Refrig.*, vol. 133, no. March 2021, pp. 247–258, 2022, doi: 10.1016/j.ijrefrig.2021.10.004.
- [16] E. Biçen and S. K. Arabacı, “Energy and exergy evaluation of R404A and R290 in a shelf-cooled commercial vertical deep freezer,” *Appl. Therm. Eng.*, vol. 278, no. PC, p. 127287, 2025, doi: 10.1016/j.applthermaleng.2025.127287.
- [17] M. T. Scholar, S. Naga, K. Pal, and S. Rajput, “Comparative Thermodynamic Performance Analysis of a Cascade System using Different Refrigerant Couples,” 2020.
- [18] M. Deymi-dashtebayaz, S. Maddah, and E. Fallahi, “Thermo-economic-environmental optimization of injection mass flow rate in the two-stage compression refrigeration cycle (Case study : Mobarakeh steel company in Isfahan , Iran) Optimisation thermo-économico-environnementale du débit massique d ’ injectio,” *Int. J. Refrig.*, vol. 106, pp. 7–17, 2019, doi: 10.1016/j.ijrefrig.2019.06.020.
- [19] G. Shanmugasundar, K. Logesh, R. Cep, and R. Roy, “Evaluating Eco-Friendly Refrigerant Alternatives for Cascade Refrigeration Systems : A Thermoeconomic Analysis,” 2023.
- [20] M. Jeon, “Refrigeration System with Internal Heat Exchanger . Part 2 ;,” 2022.
- [21] S. Chaturvedi, N. K. Sharma, and C. Ranganayakulu, “Exergy analysis and performance evaluation of a vapor compression refrigeration system using R-134a , R-600a , and R-125,” *Int. J. Refrig.*, vol. 175, no. October 2024, pp. 74–84, 2025, doi: 10.1016/j.ijrefrig.2025.03.034.
- [22] A. G. S. Almeida and F. S. Almeida, “EXERGY ANALYSIS OF CASCADE REFRIGERATION SYSTEM FOR LOW TEMPERATURES USING ECOLOGICAL FLUIDS,” no. Cobem, pp. 10221–10230, 2013.
- [23] V. Voloshchuk, P. Gullo, E. Nikiforovich, and N. Buyak, “Simulation and exergy analysis of a refrigeration system using an open-source web-based interactive tool—comparison of the conventional approach and a novel one for avoidable exergy destruction estimation,” *Appl. Sci.*, vol. 11, no. 23, 2021, doi: 10.3390/app112311535.