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Analysis of the Coefficient of Performance in a Cascade Flash Chamber Cooling System for Fishing Vessels

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ABSTRACT

Global climate change is closely related to increasing greenhouse gas emissions, including those generated by energy-intensive refrigeration systems on fishing vessels. Conventional onboard cooling systems often operate at relatively low efficiency, resulting in high fuel consumption and environmental impact. This study aims to analyze the coefficient of performance (COP) of a cascade refrigeration system with a flash chamber for fishing vessel applications by evaluating the influence of refrigerant selection and intermediate operating temperature. A steady-state thermodynamic simulation model was developed using Engineering Equation Solver (EES). Three refrigerants, namely R134a, R404A, and R407C, were investigated under intermediate temperature variations of 10–30 °C. The model was validated through comparison with reference data from the literature. Simulation results include compressor power consumption, condenser heat rejection, evaporator heat absorption, and COP values. The results indicate that intermediate temperature significantly affects compressor work distribution between the low-stage and high-stage compressors. Among the evaluated refrigerants, R134a achieved the highest COP under all operating conditions, while R404A showed lower condenser heat rejection and cooling capacity. Overall, the cascade refrigeration system with a flash chamber demonstrates improved energy performance and offers a promising solution to reduce fuel consumption and greenhouse gas emissions in marine refrigeration applications.

KEYWORDS: *Cascade refrigeration; Coefficient of performance; Flash chamber; Fishing vessel; Refrigerant.*

NOMENCLATURE

$\dot{Q}_L$	Cooling capacity / evaporator heat absorption (kW)
$\dot{W}_{net,in}$	Total compressor power input (kW)
COP	Coefficient of Performance (–)
$\dot{m}$	Refrigerant mass flow rate (kg/s)
h_i	Specific enthalpy at state point i(kJ/kg)
HTC	High-Temperature Cycle
LTC	Low-Temperature Cycle
T_{cond}	Condensing temperature (K)
T_{evap}	Evaporating temperature (K)
T_{int}	Intermediate (flash) temperature (K)
η_{is}	Compressor isentropic efficiency (–)
$\dot{m}_B$	Refrigerant mass flow rate in the high-temperature cycle (kg/s)
$\dot{m}_A$	Refrigerant mass flow rate in the low-temperature cycle (kg/s)

1. INTRODUCTION

Global climate change has become one of the most critical global issues, primarily driven by the increasing concentration of greenhouse gases in the atmosphere. The environmental impact of these gases is commonly quantified using the Global Warming Potential (GWP), which compares their heat-trapping ability relative to carbon dioxide. The increase in greenhouse gas emissions not only affects atmospheric conditions but also significantly impacts marine ecosystems and fisheries sustainability [1]. Ocean warming and intensified fishing activities have been shown to disturb marine ecological balance, influencing fish migration patterns and long-term fish stock productivity [2]. Consequently, improving energy efficiency in fishing operations, including onboard refrigeration systems, is essential to reduce fuel consumption and associated emissions.

Fishing vessels rely heavily on refrigeration systems to maintain the freshness and quality of the catch during extended offshore operations. Conventional single-stage vapor compression refrigeration systems often exhibit relatively low Coefficient of Performance (COP), leading to high compressor power consumption and increased operational costs [3]. To address this limitation, cascade refrigeration systems have been developed to achieve lower

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temperatures with improved thermodynamic performance. A cascade system integrates two refrigeration cycles high temperature cycle (HTC) and low temperature cycle (LTC) connected through a cascade condenser, enabling better load distribution and reduced compressor stress [4].

Recent developments have focused on enhancing cascade systems through advanced configurations such as flash chambers and multi-stage compression. The inclusion of a flash chamber improves refrigerant phase separation, reduces throttling losses, and decreases compressor workload, thereby potentially increasing COP [5]. Studies on two-stage vapor compression systems with flash chambers for marine applications demonstrated that refrigerant selection and interstage pressure significantly influence system performance [6]. Similarly, parametric and optimization analyses of cascade refrigeration systems indicate that operating temperature and pressure variations strongly affect energy efficiency and exergy performance [6]. Furthermore, onboard CO_2 cascade refrigeration systems have been investigated for fishing vessels, highlighting the importance of energy-efficient refrigeration in maritime applications [7].

Despite these developments, there remains a research gap concerning the performance evaluation of cascade refrigeration systems equipped with flash chambers specifically applied to fishing vessels using commonly available HFC refrigerants such as R134a, R404A, and R407C.

Although these refrigerants have high GWP values and are being phased down under the Kigali amendment, they remain widely installed in existing fishing vessel fleets, making a thermodynamic performance baseline essential to support future transition toward lower-GWP alternatives. Most previous studies focus on natural refrigerants or industrial-scale applications, while limited research examines comparative performance under varying operational conditions relevant to fishing vessels [8]. Therefore, a systematic thermodynamic analysis considering refrigerant variation, operating temperature, and pressure conditions is required to determine the optimal configuration for marine refrigeration systems.

This study aims to analyze the Coefficient of Performance (COP) of a cascade flash chamber cooling system applied to a fishing vessel. The analysis evaluates the effects of refrigerant selection (R134a for the high-temperature cycle and R404A or R407C for the low-temperature cycle), operating temperatures, and pressure variations on system performance. The system is modeled using Engineering Equation Solver (EES) based on energy and mass balance equations. The results are expected to provide technical insights into improving refrigeration efficiency, reducing compressor power consumption, and supporting environmentally sustainable fishing vessel operations.

2. MATERIAL AND METHOD

2.1 System Configuration

This study analyzes a cascade vapor-compression refrigeration system equipped with a flash chamber for application on fishing vessels. The system consists of two thermodynamically coupled cycles: a high-temperature cycle (HTC) and a low-temperature cycle (LTC). The two cycles are interconnected through a cascade condenser, which allows heat transfer from the low-temperature refrigerant to the high-temperature refrigerant. The flash chamber is positioned at the intermediate pressure level to enhance phase separation and reduce compressor workload [9].

Figure 1 illustrates the thermodynamic flow of refrigerant through the high-pressure compressor, condenser, expansion valve, flash chamber, evaporator, and low-pressure compressor. The cascade condenser serves as the thermal bridge between the HTC and LTC. The flash chamber separates the refrigerant into saturated vapor and saturated liquid fractions at the intermediate pressure. This configuration enables improved refrigerant distribution and reduced throttling losses, which directly influence compressor power and system COP.

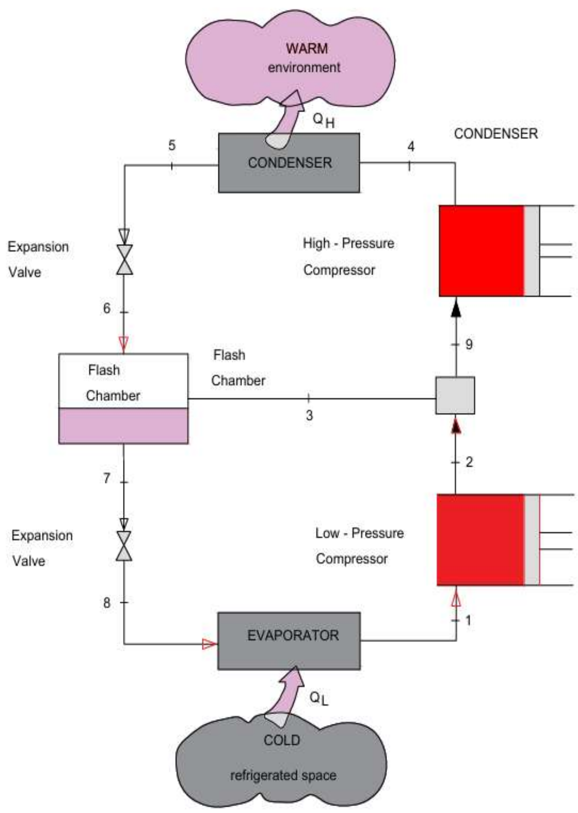

Figure 1: Schematic diagram of the cascade flash chamber refrigeration system.

2.2 Operating Conditions

The operating parameters are defined based on typical marine refrigeration conditions and previous cascade system investigations [10]. The analysis considers variations in condensation temperature, evaporation temperature, and intermediate (flash) temperature. Compressor isentropic efficiency and refrigerant mass flow rate are treated as fixed baseline assumptions.

Table 1 presents the thermodynamic boundary conditions used in the simulation. The condensation temperature varies between 308.15–313.15 K (35–40 °C), representing marine ambient conditions. The evaporation temperature ranges from 268.15–273.15 K (−5–0 °C), corresponding to low-temperature storage applications onboard fishing vessels.

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Table 1: Operating temperature ranges and simulation assumptions

Parameter	Range [K]	Range [°C]
Condensation Temperature	308.15 – 313.15 K	35 – 40 °C
Evaporation Temperature	268.15 – 273.15 K	−5 – 0 °C
Intermediate / Flash Temperature	283.15 – 303.15 K	10 – 30 °C
Subcooling Temperature	273.15 – 283.15 K	0 – 9.85 °C
Compressor Isentropic Efficiency	–	0.60 (60%)
Refrigerant Mass Flow Rate	–	0.05 kg/s

2.3 Thermodynamic Model

A steady-state thermodynamic model is developed using mass and energy conservation principles. Refrigerant properties are obtained using the Engineering Equation Solver (EES) built-in property database. The refrigeration capacity at the evaporator is calculated as:

$$\dot{Q}_L = \dot{m}_B(h_1 - h_8) \quad (1)$$

where $\dot{Q}_L$ the cooling capacity (kW), $\dot{m}_B$ the refrigerant mass flow rate in the low-temperature cycle (kg/s), and h_1 and h_8 are the refrigerant enthalpies at the evaporator inlet and outlet (kJ/kg). The total compressor power input is expressed as:

$$\dot{W}_{net,in} = \dot{m}_B(h_2 - h_1) + \dot{m}_A(h_9 - h_3) \quad (2)$$

where $\dot{m}_B$ is the refrigerant mass flow rate in the low-temperature cycle (kg/s),$\dot{m}_A$ is the refrigerant mass flow rate in the high-temperature cycle (kg/s) and h_2 ,h_6 , h_4 ,h_9 are the specific enthalpies at the corresponding state points. The system Coefficient of Performance (COP) is defined as:

$$COP = \frac{\dot{Q}_L}{\dot{W}_{net,in}} \quad (3)$$

These equations form the basis for evaluating refrigeration performance under varying operating conditions and refrigerant combinations.

2.4 Simulation Procedure

The thermodynamic equations are implemented in Engineering Equation Solver (EES) to perform parametric simulations. EES is selected due to its ability to solve coupled non-linear equations and provide accurate thermophysical property calculations for refrigerants [11]. The simulation procedure is structured as follows:

a. Definition of working fluids (R134a–R404A and R134a–R407C).
b. Input of operating conditions and assumptions (Table 1).
c. Determination of thermodynamic state properties at each point in Figure 1.
d. Calculation of cooling capacity, compressor work, and COP.
e. Parametric variation of operating temperatures to evaluate performance trends.

This study begins with the identification and formulation of the research problem related to the performance of a cascade flash chamber refrigeration system for fishing vessels, followed by a literature review to establish the theoretical basis, system configuration, and relevant operating parameters. Data are then collected to define the simulation boundaries and assumptions.

Next, the refrigeration system scheme is designed and a thermodynamic simulation is carried out using Engineering Equation Solver (EES). The simulation results are subsequently validated to ensure the reliability of the developed model; if the results are not valid, adjustments are made and the simulation is repeated until acceptable agreement is achieved. After the model is confirmed to be valid, a parametric analysis is conducted by varying the main research variables, including refrigerant mixture selection, pressure variation, and temperature variation. The simulation outputs include enthalpy, energy performance, and the Coefficient of Performance (COP), which are then analysed to evaluate the overall thermodynamic behaviour of the system and to draw final conclusions.

3. RESULT AND DISCUSSION

3.1 Model Validation

Model validation was conducted to assess the reliability of the thermodynamic simulation. The simulated COP values were compared with secondary reference data reported by Kepekci for a two-stage vapor compression refrigeration system with a flash chamber [5]. Validation was performed for three refrigerants (R134a, R404A, and R407C) under intermediate temperature variations of 10, 15, 20, 25, and 30 °C.

$$MD = \frac{1}{N}\sum_{i=1}^{N} \left| \frac{d_{pre} - d_{exp}}{d_{exp}} \right| \times 100 \quad (4)$$

The mean deviation (MD) represents the average relative difference between simulation results and reference values, where a smaller MD indicates better agreement with the literature [5].

Figure 2 shows that the simulated COP for R134a follows the same trend as the reference values across intermediate temperature, indicating that the model captures deviation (MD) for R134a is calculated at 5.99%, indicating good agreement between the simulation and the reference data.

Figure 2 confirms that the simulation results remain close to the reference values, although deviations appear at certain temperature points. These deviations can occur due to differences in modeling assumptions, compressor efficiency, or boundary conditions applied in the present simulation compared with those used in the reference study [5].

Figure 3 indicates that the simulated COP for R404A matches the reference at several temperature points, suggesting good consistency for this refrigerant under the tested intermediate conditions. The mean deviation (MD) for R404A is calculated at 2.12%, indicating excellent agreement between the simulation and the reference data.

Figure3 illustrates that the simulated curve reproduces the reference trend, supporting the suitability of the thermodynamic formulation for evaluating system performance under refrigerant variation.

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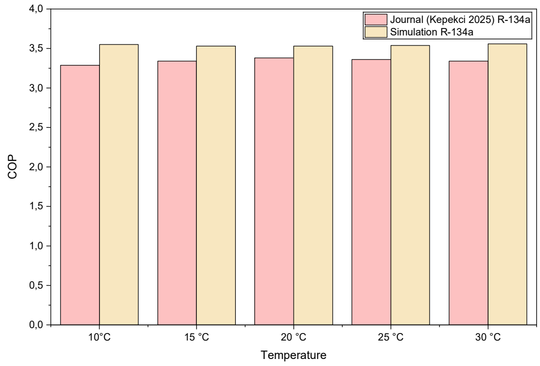

Figure 2: Validation results for R134a (COP vs intermediate temperature)

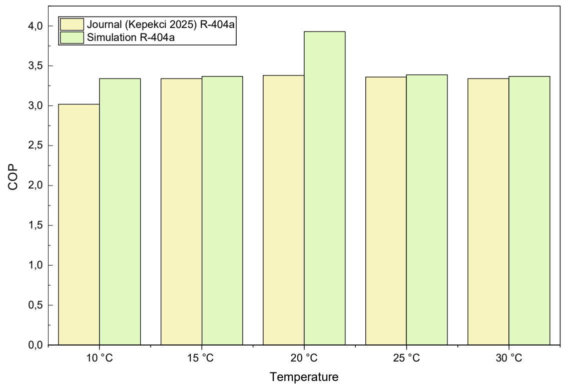

Figure 3: Validation results for R404A (COP vs intermediate temperature)

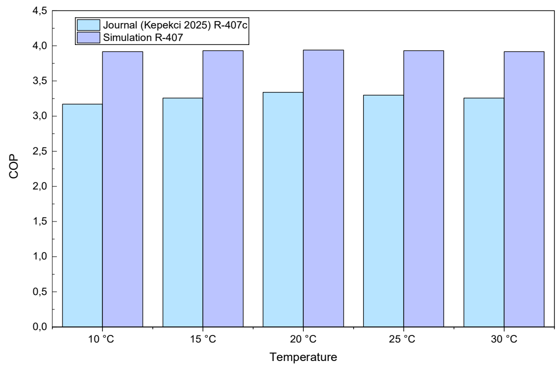

Figure 4: Validation results for R407C (COP vs intermediate temperature)

Figure 4 shows that R407 presents a large deviation compared with R134a and R404a, with a mean deviation (MD) of 19.95%. This deviation can be attributed to the zeotropic nature of R407c, which consists of R32, R125, and R134a exhibiting temperature glide during phase change. In EES simulation, refrigerant properties are evaluated under thermodynamic equilibrium assumptions, which may differ from the property evaluation approach used in the reference study. Furthermore, the assumed constant isentropic efficiency of 60% may not accurately represent the actual compressor performance for zeotropic mixture [7].

Figure 4 suggests that, despite some differences in magnitude, the simulation reproduces the general trend of COP with respect to intermediate temperature, therefore the model is considered acceptable for comparative analysis across refrigerants [5].

3.2 Compressor Power Characteristics

Compressor power is a key indicator of energy consumption in cascade systems because it directly determines the work input required to achieve the refrigeration effect. The system includes a low-temperature compressor (LTC compressor) and a high-temperature compressor (HTC compressor). The effect of intermediate temperature on compressor power for each refrigerant is presented in Figures 5, 6, and 7.

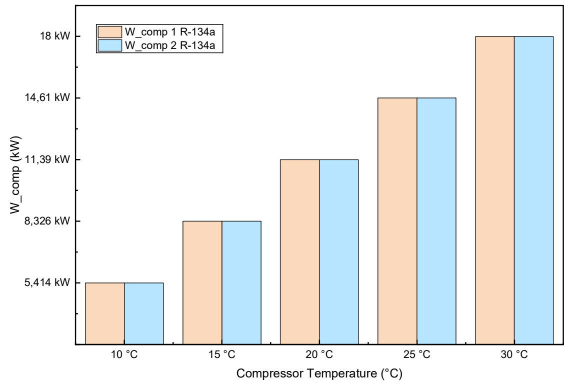

Figure 5: Effect of intermediate temperature on compressor power using R134a

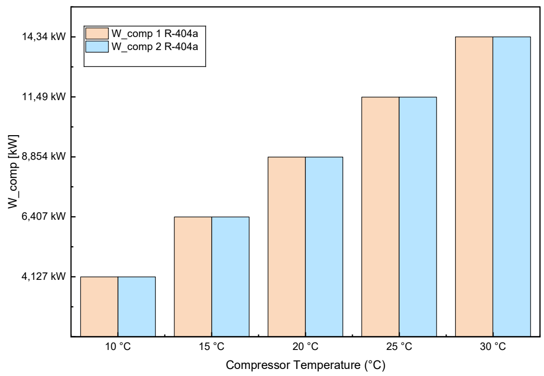

Figure 6: Effect of intermediate temperature on compressor power using R404A

Figure 5 shows that increasing intermediate temperature raises the power demand of the low-temperature compressor, while the high-temperature compressor power decreases. This behavior is consistent with changes in suction pressure and compression ratio: higher intermediate temperature increases LTC suction pressure and modifies mass distribution, increasing LTC work, whereas the effective pressure ratio for the HTC compressor becomes smaller, reducing its work requirement.

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Figure 6 indicates that R404A produces the lowest high-stage compressor power among the tested refrigerants at higher intermediate temperatures. This suggests that R404A may reduce the high-stage compression burden due to its thermodynamic characteristics under the tested operating range, consistent with observations that refrigerant selection strongly affects compressor work in two-stage flash-chamber systems [6].

Figure 7 shows the same general trend as the other refrigerants but with higher power levels, particularly for the high-stage compressor at lower intermediate temperatures. Similar findings have been reported in multi-stage or cascade cycle analyses, where refrigerant properties and pressure ratios govern total compression work and overall efficiency [4].

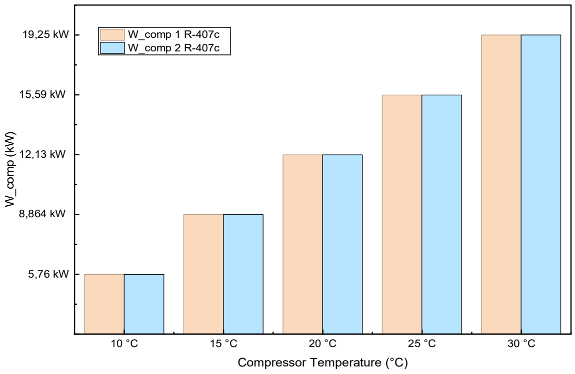

Figure 7: Effect of intermediate temperature on compressor power using R407C

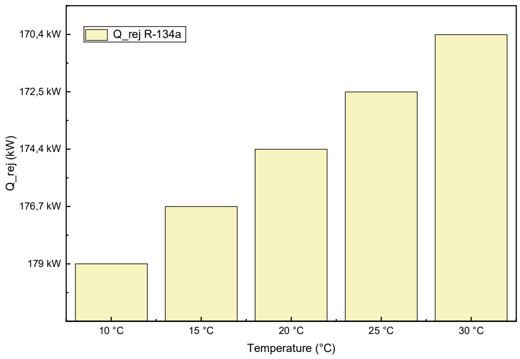

Figure 8: Effect of intermediate temperature on condenser heat rejection using R134a

3.3 Heat Rejection at the Condenser

Heat rejection at the condenser represents the thermal load that must be discharged to the environment. Lower condenser heat rejection may reduce condenser size requirements and improve overall heat management onboard. The effect of intermediate temperature on condenser heat rejection for each refrigerant is shown in Figures 8-10.

Figure 8 indicates a decreasing trend of heat rejection with increasing intermediate temperature. This can be explained by the reduced enthalpy difference across the condenser as the intermediate condition changes, resulting in lower heat that must be rejected to the environment.

Figure 9 shows that R404A consistently yields the lowest condenser heat rejection compared with R134a and R407C across the tested range. This implies a lower condenser thermal burden, which can be advantageous for marine systems where space and heat rejection capability are constrained.

Figure 10 demonstrates that R407C results in the highest condenser heat rejection among the three refrigerants, indicating a larger thermal load on the condenser. In multi-stage refrigeration systems, refrigerants that generate higher discharge enthalpy commonly led to higher heat rejection requirements [3]. Selection of refrigerants with appropriate pressure-enthalpy characteristics can therefore influence condenser design and overall energy performance [3].

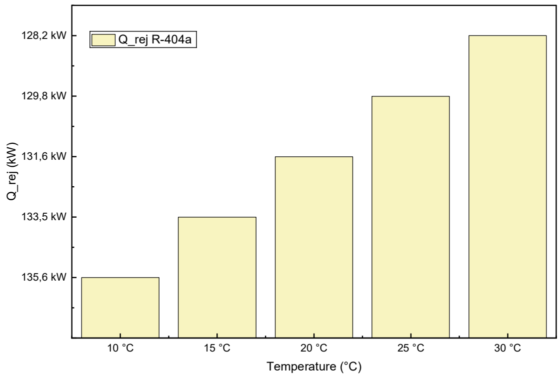

Figure 9: Effect of intermediate temperature on condenser heat rejection using R404A

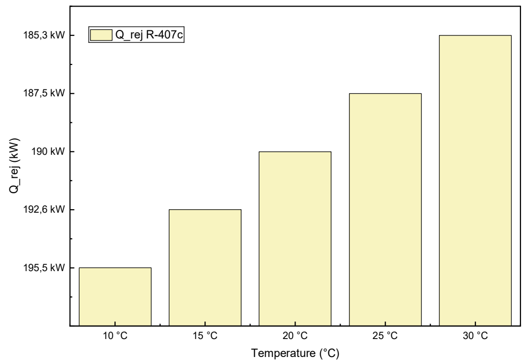

Figure 10: Effect of intermediate temperature on condenser heat rejection using R407C

3.4 Heat Absorption at the Evaporator

Evaporator heat absorption is the primary indicator of cooling capacity, representing the amount of heat removed from the refrigerated space. Figures 11-13 show the influence of intermediate temperature on evaporator heat absorption. Figure 11 shows that evaporator heat absorption for R134a remains relatively stable across the intermediate temperature range. This indicates that the refrigeration effect is not strongly affected by intermediate temperature under the fixed mass flow assumptions used in the model.

Figure 12 shows that R404A produces a lower evaporator heat absorption compared with R134a and R407C, suggesting

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a lower cooling capacity under the same conditions. Similar trends have been reported in refrigeration studies where capacity depends strongly on latent heat and enthalpy difference across the evaporator [3].

Figure 13 indicates that R407C provides evaporator heat absorption comparable to R134a and remains relatively stable. Stable heat absorption is beneficial for cold storage applications because it supports consistent temperature control. In cold-storage evaporator applications, heat transfer behavior is often more sensitive to flow and internal convection characteristics than to intermediate temperature alone, especially when mass flow is fixed [3].

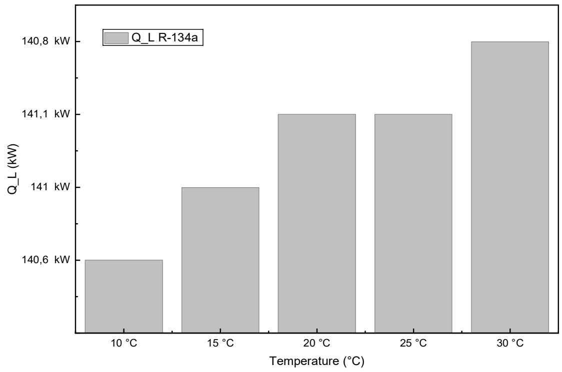

Figure 11: Effect of intermediate temperature on evaporator heat absorption using R134a

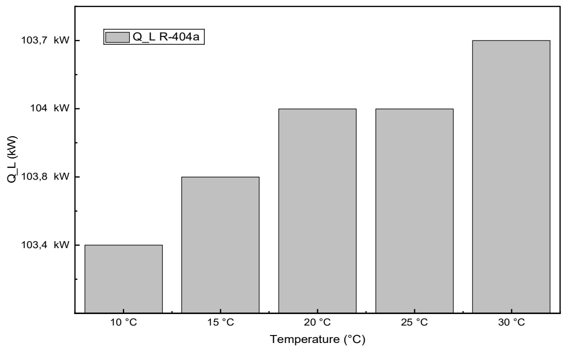

Figure 12: Effect of intermediate temperature on evaporator heat absorption using R404A

3.5 Coefficient of Performance (COP) Comparison

The COP represents the overall energy efficiency of the refrigeration system. It is determined by the ratio of evaporator heat absorption to total compressor work input. The comparative COP results of R134a, R404A, and R407C are summarized in Figure 14.

Figure 14 shows that R134a produces the highest COP across the tested intermediate temperature range, indicating superior energy performance compared with R404A and R407C under the same operating assumptions. The higher COP of R134a is associated with its relatively high and stable evaporator heat absorption combined with moderate compressor power requirements.

These results are consistent with prior findings that refrigerants with favorable thermodynamic characteristics can improve COP in two-stage flash-chamber systems, where performance depends on the balance between refrigeration effect and compression work [5]. Additionally, cascade and multistage cycle analyses highlight that refrigerant selection and cycle configuration can significantly affect overall efficiency and component loads [4].

From an application perspective, selecting a refrigerant based solely on COP is not sufficient; environmental considerations (e.g., GWP), regulatory constraints, and operational safety must also be considered. However, from a purely thermodynamic viewpoint, the present results indicate that R134a offers the most efficient performance among the evaluated refrigerants for the analyzed cascade flash chamber configuration.

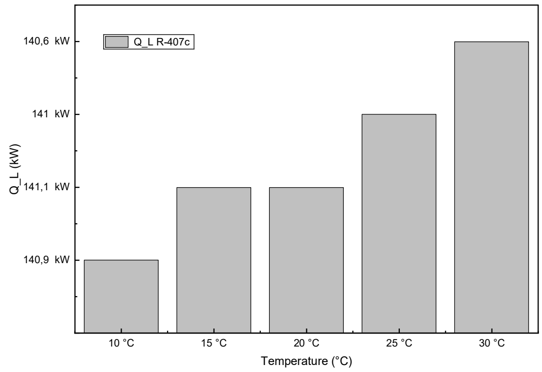

Figure 13: Effect of intermediate temperature on evaporator heat absorption using R407C

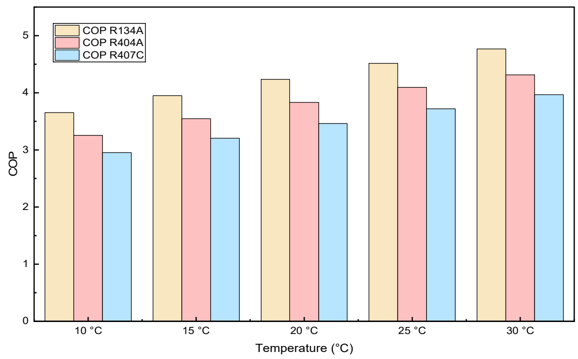

Figure 14: COP comparison across refrigerants under intermediate temperature variation

4. CONCLUSION

This study investigated the thermodynamic performance of a cascade refrigeration system equipped with a flash chamber for fishing vessel cooling applications. The results indicate that the total compressor work is significantly influenced by the combined operation of the high-temperature compressor (HTC) and low-temperature compressor (LTC). The integration of a flash chamber improves system efficiency by separating vapor and liquid phases at the intermediate pressure level, thereby reducing throttling losses and compressor workload. Proper regulation of interstage pressure and effective heat transfer in the sub cooler and desuperheater further contribute to enhanced thermal stability and improved overall system performance compared to conventional refrigeration systems.

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From a thermodynamic perspective, refrigerant selection (R134a, R404A, and R407C) has a substantial impact on the Coefficient of Performance (COP). Among the evaluated refrigerants, R134a demonstrated the highest COP values under the studied operating conditions, indicating superior energy performance in the cascade flash chamber configuration. compared with the other refrigerants considered in this study.

Overall, the cascade refrigeration system with a flash chamber demonstrates promising potential for fishing vessel cooling applications. The system provides stable low-temperature operation and improved refrigeration performance, which may contribute to more energy-efficient onboard cooling systems and support sustainable cold-chain preservation of fish products.

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