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Thermodynamic Efficiency Analysis of ORC-VCR Ship Cooling Systems with Low-GWP Fluids Based on Ship Engine Waste Heat

Colin Steven Aruan, Fajri Ashfi Rayhan*

Department of Naval Architecture, Faculty of Engineering, Universitas Pembangunan Nasional Veteran Jakarta, Jakarta, 12450, Indonesia

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ABSTRACT: The growing demand for efficient onboard air-conditioning systems has encouraged the exploration of alternative energy recovery approaches in maritime operations. In this context, the present work evaluates a hybrid ORC-VCR system that harnesses waste heat from engine exhaust gases and cooling water circuits to support shipboard climate control. A comprehensive thermodynamic framework is established to assess and compare the operational performance of three working fluids: R601, R1233zd, and R1234ze. To enhance overall system effectiveness, an optimization analysis is carried out to evaluate various working fluids and define the operating parameters that enable the highest achievable efficiency. The analysis considers key parameters, including heat source temperature, condensing temperature, as well as hot water mass flow rate levels. Analysis outcomes demonstrate that variations in working fluid selection lead to significant differences in overall efficiency and operational performance parameters. Among the fluids evaluated, R1234ze demonstrates the highest overall performance under the examined operating conditions. In addition, system performance metrics, including output capacity and coefficient of performance, are substantially governed by variations in heat source temperature and condensing conditions. Adjustment of the hot water flow rate effectively controls the evaporator temperature, contributing to system optimization. In summary, performance assessment results indicate that R1234ze offers the greatest efficiency, making it the optimal choice for implementation in the proposed shipboard waste heat recovery system.
Keywords: thermodynamic; ORC-VCR; GWP Fluid; COP; efficiency

1. Introduction

The maritime industry faces environmental challenges as vessel cooling systems continuously dissipate substantial engine waste heat into the environment, exacerbating ecological degradation and contributing to air pollution. The (International Maritime Organization (2020) reports that total heat discharged from ship engines increased by 9.6% between 2013 and 2018, underscoring the growing importance of waste heat management in marine applications. Marine diesel engines reject a significant portion of input energy through exhaust gases and cooling systems, making waste heat recovery essential for improving onboard energy efficiency (Mariani et al., 2022; Pesyridis et al., 2023).

The increasingly severe impacts of climate change have led scientists and environmental agencies to emphasize that, without concrete measures to reduce greenhouse gas emissions, global temperatures will continue to rise. This rise is expected to intensify extreme weather events and cause more severe environmental, economic, and social consequences (Masson-Delmotte et al., 2021). Concurrently, growing global demand for cooling, driven by rising temperatures and urbanization, is projected to significantly increase energy consumption and greenhouse gas emissions, thereby heightening the need for efficient and sustainable cooling technologies (Witanowski, 2024a).

Optimizing waste heat utilization can substantially reduce or eliminate thermal energy released into the environment, mitigating the maritime sector's contribution to thermal pollution and its adverse effects on marine ecosystems and the atmosphere (Ferdyson et al., 2025). Effective recovery and conversion of excess heat enhance overall energy efficiency and promote environmental sustainability in marine operations.

The Organic Rankine Cycle (ORC) has emerged as an effective technology for capturing waste heat from marine systems, particularly when thermal energy is available at low to intermediate temperatures. However, ORC system performance in marine applications depends heavily on operating conditions, such as engine load and sailing profile, which influence the availability of the heat source and its

* Corresponding Author
Email address: fajri.ar@upnvj.ac.id

temperature (Ng et al., 2022). Additionally, thermodynamic performance is strongly affected by heat source characteristics, system configuration, and operating parameters, indicating that optimal system design must be application-specific (Yang et al., 2024).

A synergistic configuration is achieved by coupling the Organic Rankine Cycle with a Vapor Compression Refrigeration cycle, forming an ORC–VCR system that converts recovered waste heat into mechanical or electrical energy to support power generation and onboard cooling and air-conditioning demands (Sun et al., 2017). This integration has emerged as a promising solution for simultaneous waste heat recovery and cooling, improving overall system efficiency (Witanowski, 2024a). Recent studies have moved beyond basic ORC performance evaluation toward more advanced analyses, including turbine-oriented design, off-design performance, and thermo-economic optimization (Mariani et al., 2022; Pesyridis et al., 2023). Furthermore, developments have explored advanced configurations such as directly combined ORC–VCR systems and dual-evaporator refrigeration architectures to enhance both cooling performance and net power output (Bilir Sag & Isik, 2025).

Current research trends increasingly employ multi-objective optimization approaches to simultaneously maximize system efficiency, cooling capacity, and operational reliability (Witanowski, 2024b, 2024a). The ORC is a thermodynamic modification of the classical Rankine cycle that uses low-boiling-point organic working fluids to convert thermal energy at low to intermediate temperatures into useful power. This characteristic enhances the ORC's applicability in recovering and converting residual thermal energy. The system offers several advantages, including high energy utilization potential, relatively simple configuration, wide component availability, and flexible design and installation. Compared to conventional waste heat recovery systems, ORC systems generally require less maintenance and provide enhanced operational safety, making them attractive for maritime energy recovery applications (Wahile et al., 2020).

The selection of the working fluid critically influences the performance of ORC and ORC–VCR systems (Bahrami et al., 2022a). Fluid choice should not rely solely on environmental indicators such as global warming potential (GWP) but must also consider thermodynamic properties, operating pressure, safety, flammability, and techno-economic factors (Bahrami et al., 2022a). Additionally, low-GWP fluids do not exhibit uniform performance, as their thermodynamic behavior strongly depends on operating conditions and system configuration (Bahrami et al., 2022a).

The selection of R601, R1233zd(E), and R1234ze(E) is supported by their distinct thermodynamic and operational characteristics. R601 (n-pentane) is a dry hydrocarbon fluid with a critical temperature of approximately 196.7 °C, a global warming potential (GWP) of about 20, zero ozone depletion potential (ODP), and ASHRAE safety class A3, indicating excellent thermodynamic performance but high flammability. Its saturation pressure ranges from approximately 6.8 kPa at 25 °C to 367.1 kPa at 80 °C, reflecting relatively low-pressure operation suitable for low- to medium-temperature heat sources.

R1233zd(E) has a critical temperature of approximately 165.5 °C, a critical pressure near 35.7 bar, a GWP of 1-7, and an ODP of 0, with a significantly lower flammability risk. In marine ORC applications, it has demonstrated performance comparable to hydrocarbon fluids, with ORC power contributions of approximately 8.0% of engine output, indicating its suitability for ship waste heat recovery systems. It also has a lower critical temperature of approximately 109.5 °C, a GWP of about 7, zero ODP, and ASHRAE safety class A2L, indicating mild flammability. Its saturation pressure increases significantly from approximately 78.5 kPa at −25 °C to 2007.4 kPa at 80 °C, implying higher operating pressure requirements but potential advantages in refrigeration performance.

These differences illustrate that each fluid offers distinct trade-offs in thermodynamic efficiency, operating pressure, safety, and environmental impact, making comparative evaluation essential for ORC–VCR systems operating under marine waste-heat conditions. (Hu et al., 2022) explored the feasibility of harnessing waste heat from marine exhaust streams and cooling water circuits to power a coupled ORC-VCR. The performance of five candidate working fluids: R22, R141b, R236ea, R218, and R601, was comparatively analyzed over a range of operating scenarios. Under conditions of 160 °C heat input and 40 °C condensation temperature, R601 demonstrated the best thermodynamic behavior, yielding the highest COP, maximum CPRm1, and the largest CW. R601 also exhibited the highest CVPN ratio and an ORC efficiency exceeding 12% under optimal conditions. In the VCR cycle, R601 demonstrated peak performance with a COP value of 7 when operating at a heat input temperature of 160 °C and a condensing temperature of 30 °C, indicating an optimal balance between system COP, Rankine cycle efficiency, and cooling capacity per unit mass flow. Furthermore, (González et al., 2023) additional numerical modeling assessed alternative low-GWP working fluids, including R1233zd and R1234ze. A peak overall coefficient of performance (0.91) was recorded for the coupled system under conditions where the turbine and compressor exhibited isentropic efficiencies of 0.85 and 0.8, respectively. Performance evaluation at a source temperature of 140 °C and a condensation temperature of 35 °C revealed that R1233zd achieved a thermal efficiency of 11.8%, with R1234ze following closely at nearly 11% under the same conditions.

R601 is considered a benchmark dry hydrocarbon with excellent thermodynamic performance for ORC applications, although its high flammability remains a practical limitation (Mariani et al., 2022). In marine applications, R1233zd has attracted attention for its low GWP and suitability as a replacement for conventional refrigerants, such as R245fa (Seo et al., 2024). Meanwhile, R1234ze is identified as a promising alternative, with performance strongly influenced by system configuration and operating parameters (Yang et al., 2024).

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Overall, the evidence indicates that the thermodynamic effectiveness of ORC-based refrigeration configurations for onboard air conditioning strongly depends on the selection of appropriate working fluids. The transition from high-GWP refrigerants, such as R134a, relies on the continued development and deployment of environmentally friendly alternatives that offer both low global warming potential and enhanced energy efficiency (Kulkarni et al., 2023). Bahrami et al. (2022b) report emission reductions of approximately 50-84% when low-GWP fluids replace R134a and R245fa.

Despite these advances, several research gaps remain. Most studies focus primarily on power generation aspects of ORC systems, while integrated ORC–VCR applications for simultaneous power and cooling in marine environments remain limited (Mariani et al., 2022; Witanowski, 2024b). Recent research emphasizes system optimization and configuration improvements rather than detailed comparative analyses of selected working fluids under specific operating conditions (Bilir Sag & Isik, 2025; Witanowski, 2024a). Moreover, system performance is highly sensitive to parameters such as heat source temperature, condenser conditions, and pressure ratio, indicating that optimal working fluid selection must be application-specific (Witanowski, 2024a; Yang et al., 2024).

However, there is still a lack of studies that specifically evaluate and compare selected low-GWP working fluids in ORC-VCR systems under marine waste heat conditions. Therefore, it is hypothesized that these fluids will exhibit different thermodynamic performance depending on operating conditions, making their comparative evaluation essential.

This study assesses the thermodynamic behavior of an ORC–VCR-based shipboard cooling system that harnesses residual thermal energy from marine engines and incorporates environmentally friendly, low-GWP working fluids. An extensive thermodynamic modeling approach is employed to investigate the effects of working-fluid variations and key operational parameters on the system's overall energy performance and coefficient of performance (COP), with the aim of identifying the optimal configuration for maximum efficiency. The results are expected to provide a clearer basis for working-fluid selection and to support the development of more energy-efficient and environmentally sustainable shipboard cooling systems for maritime applications.

2. Materials and Methods

2.1. Configuration of the Proposed System

The proposed system consists of an integrated organic Rankine cycle-vapor compression refrigeration (ORC–VCR) system driven by waste heat from marine engine exhaust gases, as illustrated in Figure 1. The system configuration is adapted from previous studies on ship waste heat recovery systems (Hu et al., 2022).

Exhaust gases from the diesel engine exit at (point 3) and enter the heat recovery boiler at (point 5), where thermal energy is transferred to water. During this heat exchange process, the exhaust gases experience a reduction in enthalpy and entropy before being discharged through (point 4) (exhaust outlet) to the environment at a lower temperature. At (point 6), the hot water pump circulates the heated water to the generator (point 7), upper heat exchange tubes), where thermal energy is transferred into the organic working fluid. Upon absorbing heat, the organic fluid vaporizes and becomes high-pressure vapor,which is subsequently directed to the expander (point 8).

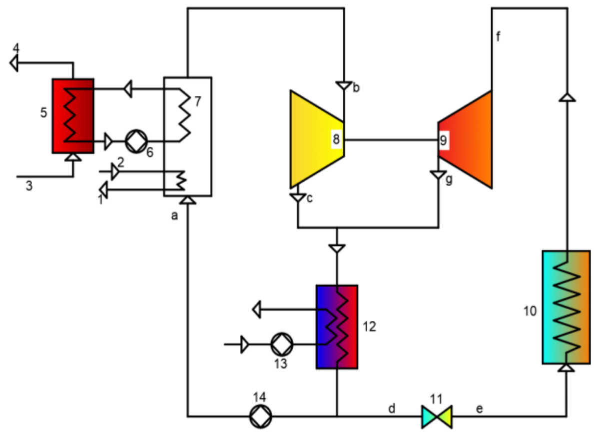

Figure 1. ORC–VCR system

Inside the expander, the high-pressure vapor undergoes expansion, resulting in an increase in specific volume and the generation of mechanical power through shaft rotation. The expanded vapor then flows to the condenser (point 12). The mechanical power produced by the expander simultaneously drives the compressor (point 9), which compresses the refrigerant to a higher pressure and temperature state before discharging it to the condenser. In the condenser (point 12), thermal energy is discharged to the cooling water delivered by the cooling water pump (point 13), causing the refrigerant to condense into a liquid state. Following condensation, the working fluid is divided into two circulation paths corresponding to the ORC and VCR subsystems.

Within the ORC subsystem, the high-pressure liquid working fluid flows into the pump (point 14), where it is elevated to the evaporation pressure and then recirculated to the generator, thereby completing the Rankine cycle. In the VCR loop (right path), the fluid passes through the throttle valve (point 11), where its pressure decreases before entering the evaporator (point 10). Within the evaporation unit, the refrigerant extracts thermal energy from the cooling medium and exits as vapor, which re-enters the compressor to continue the refrigeration cycle. This integrated configuration enhances waste heat recovery and demonstrates the thermodynamic synergy between the ORC and VCR cycles, thereby improving overall energy utilization in maritime applications.

2.2. Working Fluid Selection

According to Bahrami et al., (2022b)the working fluids R-601, R-1233zd, and R-1234ze exhibit zero ozone depletion potential (ODP) and low global warming potentials (GWP) of approximately 11, 7, and 1, respectively, making them suitable as environmentally friendly and low-emission refrigerants. R-601 and R-1234ze demonstrate satisfactory thermodynamic performance in both ORC and VCR systems operating at low to medium temperature ranges. Meanwhile, R-1233zd has been identified as an effective alternative to R-245fa, offering improved thermal stability, particularly under supercritical operating conditions. Although these working fluids are generally compatible with various refrigeration oils, compatibility assessments with specific lubricants and constructionmaterials are required to ensure reliable system operation.

Despite their environmental advantages, these fluids are classified under safety category A3 due to their flammability, necessitating enhanced safety measures for shipboard applications. R-601 poses the highest fire risk because of its pure hydrocarbon composition, whereas R-1233zd and R-1234ze also require careful risk assessment regarding flammability. In addition, R-1234ze may exhibit performance limitations in ORC systems at elevated temperatures. Owing to its thermophysical properties, the implementation of R-1233zd may also require adjustments in turbine design to ensure optimal performance and operational stability.

2.3 Thermodynamic Modelling

The thermodynamic model of the ORC–VCR system was developed based on the methodology proposed by Hu et al., (2022) . The model describes the energy balance and performance of each component within the integrated system.

2.3.1. ORC

The Organic Rankine Cycle (ORC) subsystem is modeled to evaluate its performance in recovering waste heat. The analysis is conducted using thermodynamic relations based on mass and energy balances.

$$\dot{W}_e = \dot{m}_o \cdot (h_b - h_{cs}) \cdot \eta_e \quad (1)$$

where $\dot{W}_e$ is the expander power output $[kW]$, $\dot{m}_o$ is the working fluid mass flow rate $[kg/s]$, h_b is the specific enthalpy at the expander inlet $[kJ/kg]$, h_{cs} is the specific enthalpy at the expander outlet under isentropic conditions $[kJ/kg]$, and η_e is the isentropic efficiency of the expander. The methodology adopted in this study is consistent with the framework presented by Saleh (2016) (Eq 2).

$$\dot{W}_{pw} = \dot{m}_o \cdot \frac{(h_{as} - h_d)}{\eta_{pw}} \quad (2)$$

where $\dot{W}_{pw}$ is the pump power input$[kW]$, h_{as} is the specific enthalpy at the pump outlet under isentropic conditions $[kJ/kg]$, h_d is the specific enthalpy at the pump inlet $[kJ/kg]$, while η_{pw} is the isentropic efficiency of the pump. This formulation follows the methodology proposed by Cihan & Kavasogullari (2017) Eq 3.

$$\dot{Q}_1 = \dot{m}_o \cdot (h_b - h_a) \quad (3)$$

in which $\dot{Q}_1$ is the heat input to the generator $[kW]$, and h_a is the specific enthalpy at the pump outlet $[kJ/kg]$. An identical formulation was applied in a study conducted by (Wang et al., 2011).

$$\dot{W}_o = \dot{W}_e - \dot{W}_{pw} \quad (4)$$

where $\dot{W}_o$ is the net power output of the ORC system $[kW]$. Expression consistent with the formulation applied in the research by (Li et al., 2013).

$$\eta_o = \frac{\dot{W}_o}{Q_1} \quad (5)$$

where η_o is the thermal efficiency of the ORC system. It is the same formula used in the previous study (Khatoon et al., 2021).

$$T_1 = \sqrt{T_8 T_3} \quad (6)$$

where T_1 is the generation temperature $[°C]$, T_8 is the inlet temperature of the heat source $[°C]$, and T_3 is the condensation temperature $[°C]$

$$WOm = \frac{\dot{W}_o}{\dot{m}_o} = (h_b - h_{cs}) \cdot \eta_e - \frac{(h_{as} - h_d)}{\eta_{pw}} \quad (7)$$

where WOm is the specific network output per unit mass flow rate $[kW]$.

$$SE = \frac{\sqrt{V_c}}{\sqrt[4]{1000\,(h_b - h_{cs})}} \quad (8)$$

where SE is the expander size parameter $[mm]$, and V_c is the cylinder volume of the expander $[mm^3]$.

2.3.2. Vapor Compression Refrigeration

The Vapor Compression Refrigeration (VCR) subsystem is modeled to evaluate its cooling performance under the given

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operating conditions. The analysis is carried out using thermodynamic relations based on mass and energy balances for each component of the cycle.

$$\dot{W}_c = \dot{W}_e \tag{9}$$

where $\dot{W}_c$ is the compressor power $[kW]$. The same formula was used in a study conducted by Molés et al., (2015).

$$\dot{Q}_5 = \dot{m}_v \cdot (h_f - h_e) \tag{10}$$

where, $\dot{Q}_5$ is the cooling capacity $[kW]$, $\dot{m}_v$ is the refrigerant mass flow rate h_f is the specific enthalpy at the evaporator outlet and h_e is the specific enthalpy at the evaporator inlet $[kJ/kg]$. The computational method employed aligns with that presented by Aphornratana & Sriveerakul (2010).

$$\dot{W}_c = \dot{m}_v \frac{(h_{gs} - h_f)}{\eta_c} \tag{11}$$

where h_{gs} is the specific enthalpy at the compressor outlet $[kW]$, η_c is the isentropic efficiency of the compressor.

$$COP_v = \frac{Q_5}{\dot{W}_c} \tag{12}$$

where COP_v is the coefficient of performance of the refrigeration cycle. This formulation closely follows the methodology introduced by Hu (2018).

$$PN = \frac{P_g}{P_f} \tag{13}$$

where PN is the compressor pressure ratio, P_g is the compressor discharge pressure $[kPa]$, and P_f is the compressor suction pressure $[kPa]$. The same formula was used in Saleh, (2018).

$$CVPN = \frac{COP_v}{PN} \tag{14}$$

where $CVPN$ is a combined performance index relating the refrigeration COP to the compressor pressure ratio.

2.3.4. System Performance

Following the individual analysis of the ORC and VCR subsystems, the overall performance of the integrated system is evaluated. Key performance indicators are employed to quantify the system efficiency and to assess its thermodynamic

$$COP_{sys} = \eta_o COP_v \tag{15}$$

where COP_{sys} is the overall performance coefficient of the ORC-VCR system. Similar to the study conducted by (Pektezel & Acar, 2019).

$$\dot{m}_{cw} = \frac{Q_5}{C_p\,(T_{cw1} - T_{cw2})} \tag{16}$$

Where $\dot{m}_{cw}$ is the cooling water mass flow rate [kg/s], T_{cw1}. is the inlet temperature of cooling water [°C] ,T_{cw2}. is the outlet temperature of cooling water [°C], and ,C_p is the specific heat capacity of water $[kJ/(kg \cdot K)]$

$$CW = \frac{\dot{m}_{cw}}{\dot{m}_{hw}}\, x\ 100 \tag{17}$$

where CW is the cooling water production ratio, and $\dot{m}_{hw}$ is the hot water mass flow rate $[kg/s]$.

2.4. Model Assumptions

To simplify the thermodynamic analysis, several assumptions are adopted. The system operates under steady-state conditions, while heat losses and frictional effects are neglected. Pressure drops in pipelines and components are ignored, and changes in kinetic and potential energy are considered negligible. In addition, the isentropic efficiencies of the expander, compressor, and pump are assumed to be constant, and the power consumption of the condenser is neglected.

These assumptions are commonly applied in thermodynamic analyses of ORC–VCR systems and are partially consistent with previous studies such as (Hu et al., 2022) .

2.5 Thermophysical Properties and Computational Method

The thermodynamic equations were solved using Engineering Equation Solver (EES). The unit system configuration used in this study is shown in Figure 2. This software enables the simultaneous solution of nonlinear equations and provides reliable thermophysical property data for working fluids.

The thermophysical properties, including enthalpy, entropy, pressure, and temperature, were obtained from the built-in database of EES. The interface of the thermophysical property database used in this study is presented in Figure 3. This ensures consistency and accuracy in determining the thermodynamic state points of each fluid throughout the cycle.

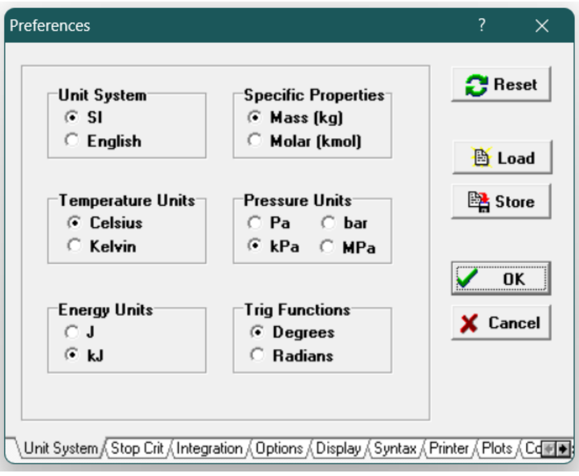

Figure 2. Unit system configuration in Engineering Equation Solver (EES)

2.6 Model Validation

Validation was performed to ensure that the simulation results are consistent with reference data, thereby confirming the reliability of the developed thermodynamic model. In this study, validation was conducted by comparing the simulation results of the efficiency ORC system using R601 (n-pentane) with the reference data reported by (Hu et al., 2022) under similar operating conditions, with heat source temperatures ranging from 80 °C to 160 °C.

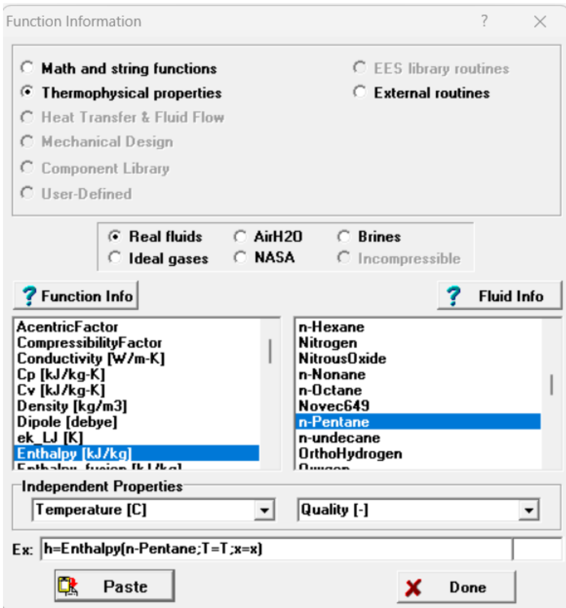

Figure 3. Thermophysical property database interface in Engineering Equation Solver (EES)

The accuracy of the model was evaluated using the Mean Deviation (MD), which represents the average deviation between the predicted (simulation) results and the reference data. The MD is calculated using the following equation:

$$MD = \frac{1}{N} \sum_{1}^{N} \left| \frac{d_{pre} - d_{exp}}{d_{exp}} \right| . 100 \qquad (18)$$

where N is the number of data point, d_{pre} is the predicted value obtained from the simulation model, and d_{exp} is the reference value obtained from the literature.

Table 1. Mean Deviation of Validation and Simulation Data

Temperature	(Hu et al., 2022)	Simulation	MD
160°C	12.57	12.55	-0.16%
140°C	11.33	11.26	-0.62%
120°C	9.75	9.67	-0.82%
100°C	7.9	7.71	-2.40%
80°C	5.35	5.3	-0.90%
	MD Total		-0.99%

The comparison results between the simulation outputs and the reference data are presented in Table 1. The calculated MD values range from -0.16% to -2.4%, with an average deviation of -0.99%

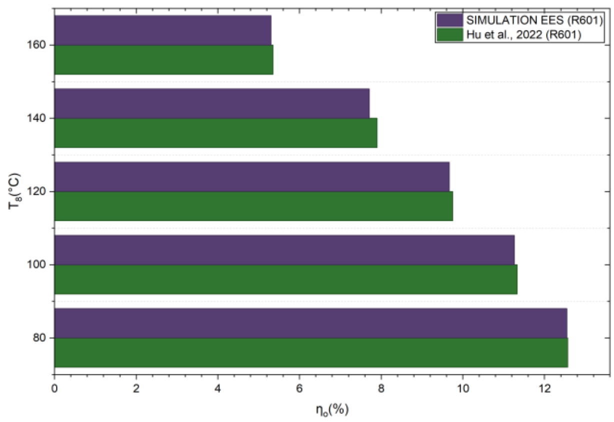

Figure 4. Comparison of ORC efficiency (η_o) between the present EES simulation and reference data from Hu et al. (2022) at different heat source temperatures

This relatively small deviation, as shown in Figure 4, indicates a strong agreement between the developed model and the reference study. The observed differences may be attributed to variations in modelling assumptions, numerical methods, and simplifications applied in the simulation process. Overall, the low deviation confirms that the developed thermodynamic model is sufficiently accurate and reliable for further performance analysis of the ORC-VCR system.

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2.7 Operating Parameter

The operating conditions used in this study are summarized in Table 2. These parameters are selected based on typical operating ranges reported in the literature (Hu et al., 2022).

Table 2. ORC-VCR Scheme Performance Parameters

Condition	Parameter
Temperature Heat Inlet Generator	80 - 160°C
Temperature Condensation	30 - 40°C
Temperature Evaporation	5°C
Inlet Water Chilled	14°C
Outlet Water Chilled	7°C
Efficiency Expander	0.85
Efficiency Compressor	0.8
Efficiency Pump	0.9
Ship Waste Heat	200 kW
Working Fluid	R601, R1233zd, dan R1234ze

In the study conducted by (Sha et al., 2025), the expander's isentropic efficiency was considered to be 86%, reflecting its high expansion performance and effective energy conversion characteristics. Such an efficiency level is considered suitable for ORC applications, contributing to improved system stability, economic feasibility, and ease of optimization in thermodynamic modeling. (Yin et al., 2021) adopted an isentropic efficiency of 80% for the compressor, based on the realistic performance range of modern compressor technologies and supported by modeling analyses and comparisons across various thermodynamic scenarios. This assumption ensures a practical representation of compressor behavior while maintaining consistency within the integrated ORC–VCR configuration. Furthermore, (Lu et al., 2024) selected an isentropic efficiency of 90% for working fluid pump in ORC system to ensure consistency in efficiency assumptions and power consumption calculations in the thermodynamic model, while accurately reflecting the technical performance of high-efficiency pumps commonly used in ORC applications.

3. Results and Discussion

3.1 Efficiency ORC

Based on the data presented in Fig. 5, it can be observed that the efficiency of the Organic Rankine Cycle (η_o) increases significantly with the rise in heat source temperature (T_8). At T_8 = 80°C, the ORC efficiency ranges from 5.30% to 5.39%, which then increases to approximately 7.71–7.90% at T_8 = 100°C, and reaches a maximum value of about 12.47–12.57% at T_8 = 160°C for all working fluids considered. This trend indicates that higher heat source temperatures provide greater thermal energy input to the evaporator, resulting in increased energy conversion into mechanical work by the expander.

As shown in Figure 5, this behavior is consistent with the thermodynamic simulation results reported by (Hu et al., 2022), which demonstrated that increasing heat source temperature enhances the enthalpy difference during the expansion process, thereby improving the overall ORC efficiency. In the present study, the obtained efficiency range is comparable to those reported in similar ORC-VCR systems operating under low-to-medium temperature heat sources, confirming the validity of the model predictions.

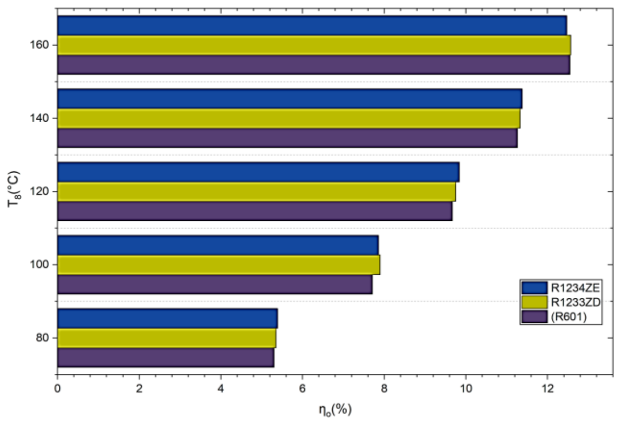

Figure 5. Effect of T_8 $(°C)$ on $\eta_o(\%)$

From a thermodynamic perspective, the increase in ORC efficiency with rising T_8 can be explained using the first law of thermodynamics applied to the organic Rankine cycle. A higher heat source temperature increases the evaporation pressure and temperature of the working fluid, leading to a larger enthalpy difference between the expander inlet and outlet. Consequently, the net work output increases without a proportional increase in heat input, resulting in higher cycle efficiency. This explanation is in agreement with the findings of (González et al., 2023), who emphasized that the performance of ORC systems is strongly influenced by the boiler or generator temperature, particularly in systems utilizing low- to medium-grade heat sources.

Furthermore, the results indicate that although different working fluids are used (R601, R1233zd, and R1234ze), the increasing trend of ORC efficiency with respect to T_8 remains consistent, with relatively small deviations between fluids. For instance, at T_8 = 140°C, the ORC efficiency ranges from 11.26% to 11.38%, while at T_8 = 160°C, it increases to 12.47–12.57%. This suggests that, within the investigated temperature range, the effect of heat source temperature is more dominant than the choice of working fluid in determining ORC performance. Similar observations were also reported by (González et al., 2023), where temperature was identified as the primary parameter governing system performance, while working fluid selection serves as a secondary optimization factor.

In addition to improving thermodynamic performance, higher heat source temperatures may also contribute to more compact system design. As reported by (Hu et al., 2022), an increase in heat source temperature leads to a reduction in expander size due to higher specific work output. This has important practical implications for marine applications, where space and weight constraints are critical design considerations. Therefore, operating at higher heat source temperatures not only enhances system efficiency but also improves the feasibility of integrating ORC-based waste heat recovery systems onboard ships.

3.2 Size Expander

The parameter T_8 represents the temperature of the heat source entering the generator and serves as a key factor influencing the expansion characteristics of the working fluid in the Organic Rankine Cycle (ORC). Based on the data presented, the variation of T_8 from 80 to 160°C shows a significant influence on the expander size parameter (SE). For all working fluids analyzed (R601, R1233zd, and R1234ze), increasing T_8 consistently leads to a reduction in SE. Specifically, for R601, SE decreases from 16.3 mm at 80°C to 9.33 mm at 160°C. Similarly, for R1233zd, SE decreases from 22.69 mm to 13.43 mm, while for R1234ze, it decreases from 22.09 mm to 13.63 mm. This reduction represents a significant decrease in expander size, indicating a substantial improvement in system compactness at higher heat source temperatures.

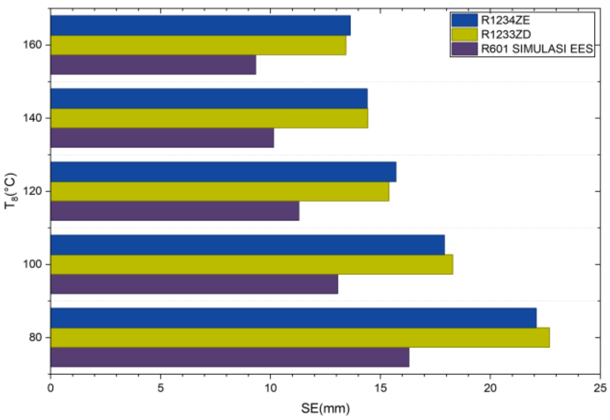

Figure 6. *Effect of* T_8 $(°C)$ on Size Expander (mm)

The reduction in expander size with increasing T_s, as illustrated in Figure 6, can be explained through thermodynamic expansion theory. As the heat source temperature increases, the enthalpy difference between the expander inlet and outlet ($h_b - h_{cs}$) becomes larger, resulting in higher specific expansion work. Consequently, the volumetric flow rate required by the expander decreases, leading to a reduction in its geometric size. This behavior is consistent with the thermodynamic model reported by (Hu et al., 2022), where an increase in heat source temperature leads to a reduction in the expander size parameter (SE) due to increased specific work output and reduced volumetric requirements.

Previous studies further support this finding. Sun et al (2017) reported that heat source temperature is a dominant parameter affecting vapor flow characteristics and expansion ratio in ORC systems. At higher temperatures, the vapor density at the expander inlet increases while the specific volume ratio decreases, resulting in smaller expander dimensions. This observation aligns with the present results, particularly in the temperature range above 120°C, where the reduction in SE becomes more pronounced and stable.

In addition, (González et al., 2023) emphasized that expander design in ORC systems is highly sensitive to heat source temperature, especially in low to medium temperature applications. An increase in temperature not only enhances expansion work but also reduces the physical size requirement of the expander and associated mechanical losses, thereby improving system compactness and design feasibility. These findings are consistent with the present study, where at T_8 = 140–160°C all working fluids exhibit minimum SE values in the range of approximately 9-14 mm.

Furthermore, the reduction in expander size at higher heat source temperatures has important practical implications for marine applications, where space and weight constraints are critical considerations. Therefore, operating at higher heat source temperatures not only improves thermodynamic performance but also enhances the feasibility of integrating ORC-based waste heat recovery systems onboard ships.

3.3 COP VCR

Based on the COPv graph, it can be observed that an increase in condensation temperature (T_3) from 30 to 40°C leads to a significant decrease in the COP of the VCR system for all refrigerants analyzed (R601, R1233zd, and R1234ze). At T_3 = 30°C, the highest COP is obtained with R601 at 8.61, followed by R1234ze at 8.33 and R1233zd at 8.10. As the condensation temperature increases to 35°C, the COP decreases to 6.65 (R601), 6.80 (R1234ze), and 6.60 (R1233zd). A further increase to T_3 = 40°C results in COP values of 5.57, 5.70, and 5.53, respectively. This represents a significant reduction in system performance, indicating a strong inverse relationship between condensation temperature and VCR efficiency.

As shown in Figure 7, from a thermodynamic perspective, this phenomenon can be explained by the increase in condensation pressure associated with higher T_3, which leads to an increase in compressor pressure ratio. As a result, the compressor work (Wc) increases, while the refrigeration effect (Q_e) tends to decrease due to the reduced enthalpy difference across the evaporator. According to the definition of COPv = Q_e/Wc, an increase in compressor work without a proportional increase in cooling capacity results in a lower COP. This behavior is consistent with the thermodynamic analysis reported by (Hu et al., 2022), who demonstrated that increasing condensation temperature significantly reduces COPv due to higher compression work and increased pressure ratio in ORC-VCR systems.

When comparing the performance of different refrigerants, R601 generally exhibits the highest COP across all T_3 variations, indicating more favorable thermophysical properties such as lower compression work and higher

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refrigeration effect. Meanwhile, R1234ze shows relatively stable performance, particularly at higher condensation temperatures (35–40°C), where it slightly outperforms R1233zd. This behavior is consistent with the findings of (González et al., 2023), which reported that HFO refrigerants such as R1234ze exhibit stable performance under moderate condensation conditions, although their maximum efficiency remains lower than that of hydrocarbon-based refrigerants.

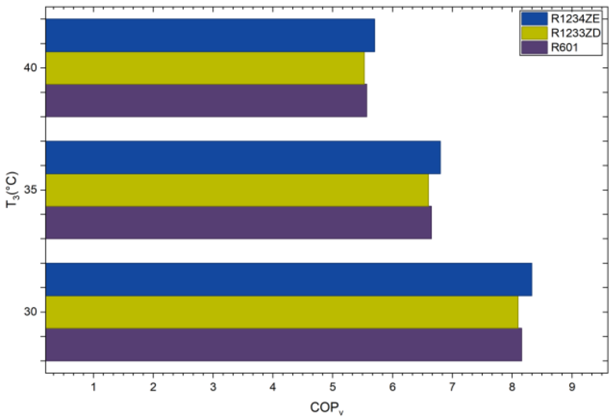

Figure 7. Effect of T_3 $(°C)$ on COP_v

In addition, the obtained results are consistent with the findings of (Kulkarni et al., 2023), which indicate that increasing condensation temperature universally leads to a reduction in COP, regardless of the type of refrigerant used. However, the magnitude of this reduction strongly depends on the thermodynamic properties of the refrigerant, including vapor density, compressibility characteristics, and enthalpy variation during compression.

Furthermore, the significant decrease in COP at higher condensation temperatures highlights the importance of maintaining optimal condenser operating conditions. This is particularly critical in marine applications, where ambient and cooling water temperatures can vary significantly. Therefore, effective thermal management of the condenser is essential to prevent performance degradation and ensure the efficient operation of ORC-VCR systems onboard ships.

3.4 COP System

Based on the graph showing the relationship between COPsystem and heat source temperature (T_8), it can be observed that increasing T_8 from 80 to 160°C has a significant impact on the overall performance of the ORC-VCR system. At T_8 = 80°C, the COPsystem values are relatively low, with 29.55% for R601, 29.83% for R1233zd, and 30.72% for R1234ze. As T_8 increases to 100°C and 120°C, the COPsystem gradually rises to a range of approximately 42.98–56.09%. The highest performance is achieved at T_8 = 160°C, where COPsystem reaches 68.97% for R601, 70.08% for R1233zd, and 71.08% for R1234ze.

This substantial increase demonstrates the strong sensitivity of overall system performance to heat source temperature. As shown in Figure 8, the increasing trend of COPsystem with respect to T_8 can be explained by the thermodynamic coupling between the ORC and VCR subsystems. As the heat source temperature increases, the ORC efficiency (η_o) improves due to the larger enthalpy difference across the expander, resulting in higher net power output. This increased power is then used to drive the compressor in the VCR cycle, enhancing the overall system performance. According to the formulation COPsystem = $\eta_o \times$ COPv, improvements in ORC performance directly contribute to higher COPsystem values. This behavior is in direct agreement with (Hu et al., 2022), who demonstrated that COPsystem increases with heat source temperature due to the combined effect of enhanced ORC efficiency and sufficient compressor driving power.

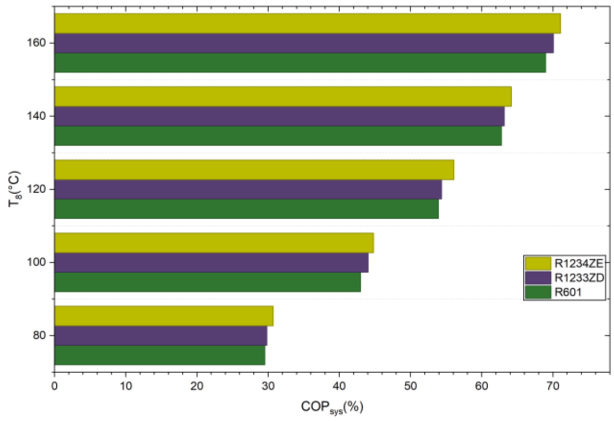

Figure 8. Effect of T_8 $(°C)$ on COP_{sys}

When comparing different working fluids, R1234ze consistently exhibits the highest COPsystem across all temperature variations, followed by R1233zd and R601. This difference indicates that although R601 may provide favorable performance in the VCR subsystem, the overall system performance depends on the combined contribution of both ORC and VCR cycles. Therefore, R1234ze shows superior performance when considering the integrated system. This observation is consistent with (González et al., 2023), which reported that HFO refrigerants such as R1234ze and R1233zd offer better thermodynamic balance and operational stability in ORC-VCR systems compared to conventional hydrocarbon refrigerants.

Furthermore, the results indicate that the selection of working fluid and heat source temperature must be considered simultaneously to achieve optimal system performance. While heat source temperature plays a dominant role, the compatibility of the working fluid with system operating conditions significantly influences the overall efficiency.

In addition, the strong dependence of COPsystem on heat source temperature highlights the importance of utilizing higher-temperature waste heat sources to maximize system efficiency. This is particularly relevant for marine applications, where the availability of waste heat varies with engine operating conditions. Therefore, optimizing heat source utilization is essential to enhance the feasibility and performance of ORC-VCR systems onboard ships.

3.5 Cooling Capacity

Based on the bar chart of evaporator temperature variation (T_{10}), it can be observed that the Cooling Capacity of the evaporator ($\dot{Q}_5$) decreases significantly as T_{10} decreases. At T_{10} = 5°C, the cooling capacity reaches its maximum for all working fluids, with values of 144.8 kW for R601, 147.8 kW for R1233zd, and 154.8 kW for R1234ze. As the evaporator temperature decreases to −15°C, the cooling capacity drops drastically to 32.33 kW (R601), 32.79 kW (R1233zd), and 35.11 kW (R1234ze). This corresponds to a reduction of approximately 77–78% across all working fluids, indicating a substantial decline in evaporator performance at lower operating temperatures.

From a thermodynamic perspective, the cooling capacity is defined as $\dot{Q}_5 = \dot{m} \times (h_f - h_e)$, where $\dot{m}$ is the refrigerant mass flow rate and $(h_f - h_e)$ represents the refrigerating effect. A decrease in evaporator temperature leads to a reduction in evaporation pressure, which in turn lowers the vapor density at the compressor inlet. This results in a reduced effective mass flow rate and a smaller enthalpy difference across the evaporator, ultimately decreasing the cooling capacity. This behavior is consistent with the thermodynamic analysis reported by (Hu et al., 2022), which highlights that $\dot{Q}_5$ is strongly influenced by both the enthalpy difference and the refrigerant mass flow rate within the ORC-VCR system.

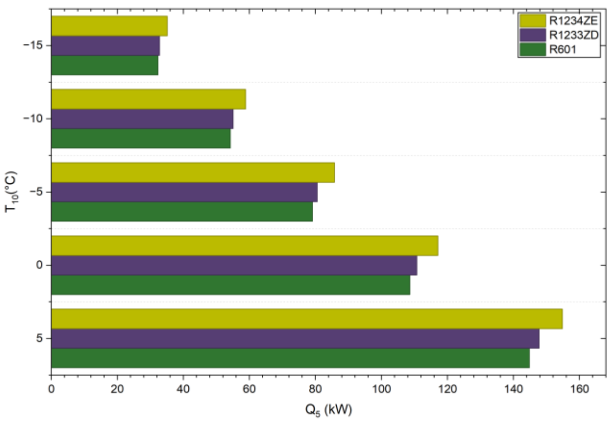

Figure 9. Effect of T_{10} $(°C)$ on $\dot{Q}_5$ $[kW]$

As shown in Figure 9, the variation of cooling capacity with decreasing T_{10} also shows a consistent trend across all working fluids, indicating that evaporator temperature plays a dominant role compared to fluid type under the investigated conditions. For example, in the case of R1234ze, $\dot{Q}_5$ decreases from 154.8 kW at 5°C to 117.1 kW at 0°C, 85.79 kW at −5°C, 58.88 kW at −10°C, and 35.11 kW at −15°C, demonstrating a progressive reduction as temperature decreases. Similar trends are observed for R1233zd and R601, confirming the general behavior of the system.

These findings are supported by González et al. (2023), who reported that lower evaporator temperatures can alter thermodynamic conditions and increase compressor energy demand, thereby reducing system performance. In addition, Kulkarni et al. (2023) showed that decreasing evaporator temperature tends to reduce the refrigerating effect and increase compression difficulty, resulting in lower cooling capacity and overall system efficiency.

Furthermore, the significant reduction in cooling capacity at lower evaporator temperatures highlights the importance of maintaining optimal evaporator operating conditions. This is particularly critical in marine applications, where environmental and operational variations can affect system performance. Therefore, selecting an appropriate evaporator temperature is essential to ensure sufficient cooling capacity and efficient operation of ORC-VCR systems onboard ships.

4. Conclusions

With respect to ORC efficiency, the differences between the evaluated working fluids are relatively small across all operating conditions. This indicates that, within the investigated heat source temperature range, ORC performance is more strongly influenced by heat source temperature than by working fluid selection. An inverse relationship is observed between heat source temperature and the expander size parameter (SE), where higher temperatures lead to lower SE values for all working fluids. This trend indicates that increased thermal input enhances specific expansion work and allows for more compact expander design.

In terms of VCR performance, R1234ze achieves the highest COP under low condensation temperature conditions and maintains stable and competitive performance across a wide range of condensation temperatures. This behavior suggests its strong adaptability to practical marine operating conditions. As an indicator of overall system performance, R1234ze consistently yields the highest COPsystem among all evaluated working fluids. It also demonstrates superior cooling capacity under all operating conditions, indicating better thermodynamic balance and more stable refrigeration performance. Overall, these results confirm that R1234ze is the most suitable working fluid for the proposed ORC–VCR system under the investigated conditions.

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Statement

The manuscript was edited for English language clarity using ChatGPT under the authors' direct supervision. Artificial intelligence tools were employed exclusively for language enhancement. All scientific analyses, data

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processing, modeling, result interpretation, and conclusions were conducted and verified solely by the authors.

Credit Authorship Contribution Statement

Colin Steven Aruan: Conceptual design, Method development, Investigation process, Data management, Formal evaluation, Preparation of the original manuscript draft. **Fajri Ashfi Rayhan**: Supervision, Validation, Manuscript review, and editorial revision.

Declaration of Competing Interests

The authors confirm the absence of any known financial or personal relationships that could potentially bias or influence the work described in this paper.

Data Availability

All datasets produced as part of this investigation originated from thermodynamic simulations and are available within the published manuscript.

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