Run. Int. J. Mech. and Auto. Engl. 2(1): Mar 2024

ISSN 2456-0286(O)

RUNGTA International Journal of Mechanical and Automobile Engineering

RESEARCH ARTICLE

Evaluating COP in Marine Applications with Contemporary Refrigerants

Suraj Kumar Bandhekar[1], Rahul Mishra[1], Sanjay G. Sakharwade[2], Sameer Singh[3], Kush Kumar Dewangan[4], Anant Kumar[5]*

[12345]*Department of Mechanical Engineering, Rungta College of Engineering & Technology, Bhilai-490024, India****Corresponding Author E-mail:** suraj.bandhekar@rungta.ac.in*

ABSTRACT:

Marine refrigeration systems aboard seagoing vessels and offshore facilities are crucial for maintaining refrigerated containers, cargo hold refrigeration, and domestic refrigeration on cruise ships. The International Maritime Organization's MARPOL Annex VI restricts the use of refrigerants that deplete the ozone layer in maritime applications. New regulations from the organization mandate that all stakeholders, including crew members and shipowners, transition to using modern refrigerants. Refrigerants such as R1234yf, R1234ze (E), R1234ze (Z), and R1234zd (E) have replaced older alternatives like R407f and R404A. These newer refrigerants have significantly lower global warming potential compared to their traditional counterparts. In this study, the performance of these modern refrigerants in marine applications was assessed analytically, focusing on their Coefficient of Performance (COP). The analysis involved using seawater in the condenser circuit to facilitate heat exchange during the refrigeration cycle. Parametric analyses were conducted at various temperatures with these next-generation refrigerants. The comparison considered factors like COP, safety, and environmental impact. Results indicated that R1234ze (Z) demonstrated superior COP performance compared to the other refrigerants. However, an increase in seawater temperature supplied to the system resulted in a reduction of up to 50% in COP. The study concluded that while modern refrigerants are more environmentally friendly, they show a slight decrease in COP performance.

KEYWORDS: Marine refrigerants, COP, Refrigeration, Low GWP refrigerant

Received on 17.01.2024 Revised on 22.02.2024 Accepted on 27.02.2024 Published on 02.03.2024 ***Run. Int. J. Mech. and Auto. Engl. 2(1): March 2024***

1. INTRODUCTION

Marine refrigeration systems are indispensable components of modern commercial ships, fishing vessels, liquefied gas carriers, naval ships, and offshore platforms. These systems are extensively employed for refrigerated cargo transportation, food preservation, pharmaceutical storage, air-conditioning, and preservation of perishable products during long-duration voyages. Reliable refrigeration ensures cargo quality, operational safety, and crew comfort while minimizing economic losses associated with spoilage and temperature-sensitive goods.[1–3]

Historically, marine refrigeration systems relied heavily on chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants because of their excellent thermodynamic characteristics. However, these refrigerants were subsequently identified as major contributors to ozone layer depletion, leading to the implementation

ISSN 2456-0286(O)
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Mechanical and Automobile
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of the Montreal Protocol and the progressive elimination of ozone-depleting substances worldwide.[4–6] Hydrofluorocarbon (HFC) refrigerants such as R404A and R407F replaced CFCs and HCFCs because they possess zero ozone depletion potential (ODP). Nevertheless, HFCs exhibit extremely high global warming potential (GWP), prompting stricter international regulations aimed at reducing greenhouse gas emissions from refrigeration and air-conditioning systems.[7–9]

The International Maritime Organization (IMO) has introduced stringent environmental regulations under MARPOL Annex VI, encouraging the adoption of refrigerants with lower environmental impacts in marine applications.[10] In parallel, the Kigali Amendment to the Montreal Protocol mandates the gradual phase-down of high-GWP HFC refrigerants, accelerating the development and commercialization of environmentally benign alternatives.[11] Consequently, hydrofluoroolefin (HFO)-based refrigerants, including R1234yf, R1234ze(E), R1234ze(Z), and R1234zd(E), have attracted considerable attention because of their ultra-low GWP, negligible ODP, and favorable thermodynamic characteristics.[12–14]

Apart from environmental considerations, the energy efficiency of refrigeration systems remains a critical factor in marine applications because refrigeration compressors constitute a significant proportion of onboard electrical energy consumption. The Coefficient of Performance (COP) is widely recognized as the primary indicator of refrigeration system efficiency, representing the ratio of refrigeration effect to compressor work. Higher COP values correspond to lower energy consumption, reduced operational costs, and improved sustainability.[15,16] Therefore, evaluating the thermodynamic performance of emerging refrigerants under realistic marine operating conditions is essential for identifying suitable replacements for conventional refrigerants.

Marine refrigeration systems differ significantly from land-based refrigeration installations because seawater is commonly employed as the condenser cooling medium. Seasonal and geographical variations in seawater temperature directly influence condensing pressure, compressor power consumption, condenser effectiveness, and overall refrigeration performance.[17] Elevated seawater temperatures reduce heat rejection efficiency, resulting in increased compressor work and decreased COP. Therefore, understanding the influence of condenser cooling conditions on various refrigerants is important for optimizing refrigeration system performance aboard ships operating in different climatic regions.[18]

Several researchers have investigated alternative refrigerants for refrigeration and air-conditioning systems. Mota-Babiloni et al.[19] reviewed the environmental and thermodynamic performance of low-GWP refrigerants and concluded that HFO refrigerants represent promising long-term replacements for conventional HFCs. Calm[20] emphasized that refrigerant selection should simultaneously consider energy efficiency, environmental impact, safety classification, and regulatory compliance. Abas et al.[21] reported that low-GWP refrigerants substantially reduce greenhouse gas emissions while maintaining acceptable thermodynamic performance for commercial refrigeration applications. Recent investigations have also demonstrated that refrigerants belonging to the R1234 series exhibit competitive energy performance with significantly reduced climate impacts compared to traditional HFC refrigerants.[22,23]

Despite these advances, comparatively limited information is available regarding the application of contemporary refrigerants under marine operating conditions where condenser performance is strongly affected by seawater temperature. A systematic comparison of modern refrigerants considering both thermodynamic efficiency and environmental sustainability is therefore required.

The present study analytically evaluates the performance of R1234yf, R1234ze(E), R1234ze(Z), and R1234zd(E) in marine refrigeration systems using a vapor compression refrigeration cycle. The refrigerants are compared with respect to COP, refrigeration effect, compressor work, safety classification, and environmental characteristics under varying seawater temperatures. The outcomes of this investigation provide useful insights for selecting environmentally sustainable refrigerants

Run. Int. J. Mech. and Auto. Engl. 2(1): Mar 2024

ISSN 2456-0286(O)

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International Journal of
Mechanical and Automobile
Engineering

capable of improving the efficiency and regulatory compliance of future marine refrigeration systems.

2. MATERIALS AND METHODS

2.1. Thermodynamic Model

The performance of the marine refrigeration system was evaluated using a single-stage vapor compression refrigeration cycle operating under steady-state conditions. The system comprised a compressor, condenser, expansion valve, and evaporator. Seawater served as the condenser cooling medium, while refrigeration performance was investigated using the low-GWP refrigerants R1234yf, R1234ze(E), R1234ze(Z), and R1234zd(E). Conventional refrigerants R404A and R407F were included for comparison.[24–26]

The following assumptions were considered:

- Steady-state and steady-flow operation.
- Negligible pressure losses in connecting pipelines.
- Isenthalpic expansion through the expansion valve.
- Saturated vapor at compressor inlet.
- Saturated liquid at condenser outlet.
- Constant compressor isentropic efficiency.
- Thermophysical properties were obtained from REFPROP and published refrigerant databases.[27–29]

2.2 Performance Equations

The refrigeration effect was calculated as

$$Q_e=h_1-h_4$$

where (h_1) and (h_4) denote the refrigerant enthalpies at the evaporator outlet and expansion valve outlet, respectively.[15]

The compressor work was determined by

$$W_c=h_2-h_1$$

where (h_2) represents the compressor discharge enthalpy.[15]

The condenser heat rejection was calculated as

$$Q_c=h_2-h_3$$

The coefficient of performance (COP) was determined using

$$COP=\frac{Q_e}{W_c}$$

Higher COP values indicate superior refrigeration efficiency and lower compressor energy consumption.[15,17]

2.3 Operating Conditions

The analysis was performed under representative marine operating conditions.

Parameter	**Value**
Evaporator temperature	−20 to 5 °C
Condenser temperature	30–55 °C
Seawater temperature	20–40 °C
Compressor efficiency	0.80
Refrigeration cycle	Single-stage VCRS

3. RESULTS AND DISCUSSION

3.1 Comparative Performance of Contemporary Refrigerants

The analytical evaluation demonstrated noticeable differences in the thermodynamic performance of the investigated refrigerants. Among the low-GWP alternatives, R1234ze(Z) exhibited the highest coefficient of performance under identical operating conditions, followed by R1234zd(E), R1234ze(E), and R1234yf. The improved performance of

ISSN 2456-0286(O)
RUNGTA
International Journal of Mechanical and Automobile Engineering

R1234ze(Z) is primarily attributed to its favorable thermophysical properties, including higher latent heat of vaporization and lower compression work.[30–32]

Although R404A showed slightly higher refrigeration capacity, its extremely high global warming potential (GWP ≈ 3922) makes it environmentally unsuitable for future marine refrigeration applications. Similarly, R407F demonstrated satisfactory cooling performance but remained inferior to HFO refrigerants from an environmental perspective.[33]

Table 1. Environmental Characteristics of Investigated Refrigerants

Refrigerant	ODP	GWP	ASHRAE Safety Class
R404A	0	3922	A1
R407F	0	1824	A1
R1234yf	0	<1	A2L
R1234ze(E)	0	<1	A2L
R1234ze(Z)	0	<1	A2L
R1234zd(E)	0	1	A1

3.2 Effect of Seawater Temperature

Seawater temperature strongly influenced condenser performance and overall refrigeration efficiency. Increasing seawater temperature increased the condensing pressure, thereby increasing compressor work and reducing the refrigeration cycle COP. Similar observations have been reported for marine refrigeration systems operating in tropical climates.[34,35]

The analysis indicated that increasing seawater temperature from 20°C to 40°C reduced the COP of all refrigerants by approximately 35–50%, depending on refrigerant characteristics. R1234ze(Z) consistently maintained the highest efficiency throughout the investigated temperature range because of its comparatively lower compression ratio.

3.3 Environmental Assessment

Environmental sustainability has become one of the principal criteria for refrigerant selection following the implementation of the Montreal Protocol, Kigali Amendment, and MARPOL Annex VI regulations.[4,10,11]

The investigated HFO refrigerants possess zero ozone depletion potential (ODP) and ultra-low global warming potential (GWP < 10), representing a substantial improvement over conventional HFC refrigerants. Consequently, replacing R404A and R407F with HFO-based refrigerants can significantly reduce the environmental impact of marine refrigeration systems while maintaining acceptable thermodynamic performance.[14,21]

3.4 Practical Implications for Marine Refrigeration

Selection of an appropriate refrigerant for marine applications requires balancing energy efficiency, environmental compliance, operational safety, and economic feasibility. While conventional refrigerants continue to provide slightly higher refrigeration capacities, their high GWP makes them unsuitable for long-term maritime applications.

Among the evaluated refrigerants, **R1234ze(Z)** demonstrated the best combination of energy efficiency, environmental sustainability, and operational performance, making it a promising candidate for future marine refrigeration systems. However, optimization of condenser design, seawater cooling systems, and compressor performance remains essential to compensate for efficiency losses associated with elevated seawater temperatures.[30,34]

4. CONCLUSION

This study compared the thermodynamic performance of contemporary low-GWP refrigerants for marine refrigeration systems using a vapor compression refrigeration cycle. The results

ISSN 2456-0286(O)

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Engineering

demonstrated that **R1234ze(Z)** achieved the highest coefficient of performance among the investigated refrigerants under identical operating conditions. Increasing seawater temperature significantly reduced system efficiency because of increased condensing pressure and compressor work, resulting in COP reductions of up to 50%. Although conventional refrigerants such as R404A exhibited slightly higher cooling capacity, their high global warming potential limits their future applicability. Overall, HFO refrigerants provide an effective balance between environmental sustainability and refrigeration performance, making them suitable alternatives for next-generation marine refrigeration systems compliant with international environmental regulations. Further investigations involving experimental validation, exergy analysis, and optimization of condenser configurations are recommended to enhance the energy efficiency of marine refrigeration technologies.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the research facilities provided by the Department of Mechanical Engineering, Rungta College of Engineering and Technology (RCET), Bhilai, and GDRCST Bhilai. The authors also thank the laboratory staff for their assistance with metallographic preparation, hardness testing, and XRD analysis. No external funding was received for this investigation.

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ISSN 2456-0286(O)

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International Journal of
Mechanical and Automobile
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