PAPER ID: 0625
DOI: 10.18462/iir.compr.2024.0625

Analysis of methods to improve the energy efficiency for sustainable marine solutions

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ABSTRACT

The study explored legislative database for maritime sector to be sustainable and have intact blue economy. The problem for organizations, ship owners having fishing carriers older than 20 years is lighted up and following challenges come to decision-making authority. In order to be in fleet for next decade, ship owners for their ships should to deploy energy efficiency projects for marine system retrofitting to improve energy efficiency and to meet environmental regulations. Ship Energy Efficiency Management Plan development principles is discussed due to currently needs for its deployment from 2023 that ship owner can contribute to fast adoption of new regulations by International Maritime Organization. Energy audit is performed and it is proposed energy efficiency program with guideline for upcoming regulations and that are currently in force. In order to improve energy efficiency, to reduce environmental impact and to cut fuel consumption costs marine system retrofitting is done, in particular case, it is proposed two options. First option is cascade refrigeration system with hydrocarbons and carbon dioxide, where ship owner win about 20% on energy efficiency improvement. Second option is two-stage refrigeration system with ammonium as the environmentally friendly refrigerant and get about 26% on energy efficiency. Technical and economic issues have been discussed. It is put focus during study on not only energy audit but energy management that can become crucial part for organization to win through integrating properly energy policy and high-quality communication concerning energy efficiency issues. Marine plastic debris challenges are faced fishing carries on the African Union rote and its possible solution that can be beneficial for ship owners is discussed.
Keywords: Energy Efficiency, Thermodynamic and Exergy Analysis, Combined Compression-Ejector Refrigeration Machine, Digitization, Optimization, Sustainable Development.

INTRODUCTION

The potential impact of new International Maritime Organization (IMO) regulations on refrigerated vessels used for transporting perishable goods in 2023-2024 is under scrutiny. The study highlights concern regarding the potential decommissioning of conventional refrigerated vessels due to new IMO regulations on environmental pollution, particularly focusing on the Carbon Intensity Indicator (CII). Vessels are classified and rated (A, B, C, D, E) based on their CII performance levels, with lower ratings necessitating improvement plans such as hull cleaning, speed optimisation, energy-efficient lighting, effective cooling, and the adoption of low-carbon fuels [1].

Commencing from January 2023, the Energy Efficiency Existing Ship Index (EEXI) regulations have been implemented. These regulations may require older vessels to reduce speed, potentially impacting their ability to meet market demand for perishable goods with limited shelf life [2].

A marine refrigeration system energy audit has been conducted, revealing potential energy efficiency improvements. Through a scientific approach employing energy and exergy analyses, results have been obtained, and opportunities to enhance energy efficiency and reduce environmental impact in accordance with ecological and energy regulations have been suggested. Implementation of best practices in energy management and auditing is advised for the refrigerated vessel and its owning company. Collaboration with the International Maritime Organization (IMO) is proposed to adapt the ship's energy efficiency management plan to comply with industry standards [3].

A holistic approach to energy efficiency management is recommended, encompassing both technological upgrades (cooling system modernisation) and strategic measures (smart energy management). A proactive stance is advocated, encouraging ship owners to consider and implement these energy-efficient measures. It is suggested to integrate a comprehensive energy efficiency management plan for vessels, including modernising or optimising cooling systems, complying with environmental standards, and utilising intelligent energy management methods [4-6].

1. THE ENERGY AND EXERGY ANALYSES OF THE VAPOUR COMPRESSION REFRIGERATION SYSTEM

An energy audit of the refrigeration system of a refrigerated vessels with a gross tonnage of 4000, flagged in Poland, was conducted. The energy potential and environmental impact potential were identified. Recommendations for managing the energy efficiency of the refrigerated vessel were proposed [7-8].

The energy [Yalama et al., 2022] and the exergy analyses of the VCRS have been investigated for four different refrigeration systems in order to find the optimal VCRS for marine refrigeration transport (fishing carrier). Our studies of an existing marine single-stage refrigeration system have shown that the transition to two-stage compression by installing additional compressors will increase the system's performance and provide a more uniform load on the compressors when operating conditions on the ship change [9-11].

Exergy destruction is a negative phenomenon in terms of the system. The system's irreversibility increasing in own turn increases exergy destruction. The results of the calculation as shown in [7], for the two-stage VCRS results present 39% reduction in exergy.

In the investigated basic VCRS, the working substance vapor is compressed in the compressor from the pressure p_e to the pressure p_c. The compressed superheated vapor, with a high temperature (discharge temperature of the compressor t_2) ranging from 80°C to 100°C and correspondingly high specific exergy, then enters the condenser, where, through irreversible heat exchange with the cooling medium, the vapor is cooled and condensed. The exergy of the rejected heat is transferred to the surrounding environment and irreversibly lost.

A thermodynamic analysis of the VCRS cycles was conducted for the combined cold and heat generation to determine the possibility of transforming this heat into cold using the ejector refrigeration (ER) system. For example, (Sun, 1998) studied a combined compression ejector refrigeration system in which an inner heat exchanger was used to combine the vapor compression cycle and the ejector cycle [12]. (Huang, et al., 2001) proposed a combined cycle refrigeration system (CCRS) that combines a conventional refrigeration and air conditioning by using a mechanical compressor and an ejector cooling cycle [13]. By considering the published literature, there be no doubt that use of combined compression ejector refrigeration (CCER) systems would exhibit a reasonable performance. Although, CCER systems have been studied from different angles, but a use of an ejector refrigeration system as a way to improve the performance of R22 system have not yet been performed and needs to be considered. In order to do so, a combined compression ejector refrigeration system with R22 refrigerant with dual cooling temperature that combines a basic VCR system with an ejector refrigeration (ER) system is described in this paper (see Figure 1). The ER system is driven thermally by the superheated vapor's waste heat from the R22 VCR system [14-15]. Figure 3 depicts a schematic solution for a combined CER system, illustrating a hybrid refrigeration system comprising a basic VCR system with an ER system. The operation of the basic VCR system is outlined as follows: Vapor generated in the evaporator 1 is compressed in the booster compressor 2 and proceeds to the generator-cooler 3, where most of the superheating heat is removed. The cooled vapor then enters the condenser 4 for further cooling and condensation at temperature tc. The liquid refrigerant from condenser 4 undergoes subcooling in the evaporator-subcooler 5, then passes through the precooler 6 for additional temperature reduction before entering the throttle valve 7. Finally, the liquid refrigerant enters the evaporator 8 to produce cold. Vapor generated in the evaporator is routed to the precooler for superheating before being drawn into the booster compressor 1.The ER system functions as the upper stage of the cascade, with its operation as follows: Saturated working vapor of the refrigerant, with temperature tG, is produced in the generator-cooler 4' due to the heat input from the superheated vapor of the compression cycle. This vapor enters the nozzle of the ejector 1', expands within it, and draws in cold vapor from the evaporator-subcooler 9'. The compressed vapor mixture in the ejector's diffuser 2' then enters the condenser 3', where it liquefies at temperature tc. The liquid leaving the condenser 3' is divided into two streams, with one flow directed to the precooler 6', where the liquid temperature is further reduced and enters the throttle valve 7. The liquid then enters the evaporator-subcooler 8', while the second stream, facilitated by the feed thermo-pump 4' operating on the float-lever principle, returns to the generator-cooler 1'.

In contrast to a traditional cascade machine, the proposed CCER system incorporates two separate condensers for each stage, dissipating heat to the environment at identical temperatures tc. Additionally, it features two combined heat exchangers - the generator-cooler and the evaporator-subcooler - facilitating heat dissipation from the lower stage to the upper stage at different temperature levels, respectively, above and below the temperature tc. Consequently, in the CCER system, the heat from the compressed superheated vapor is effectively utilised for the operation of the upper stage, while the cold obtained in the ER system is employed to subcool the liquid refrigerant after the condenser of the lower stage. This results in an enhancement of the coefficient of performance of the VCRS.

The CCER system can serve as a supplementary system to support the implementation of R22 VCR systems and reduce the consumption of limited fuel supplies on vessels.

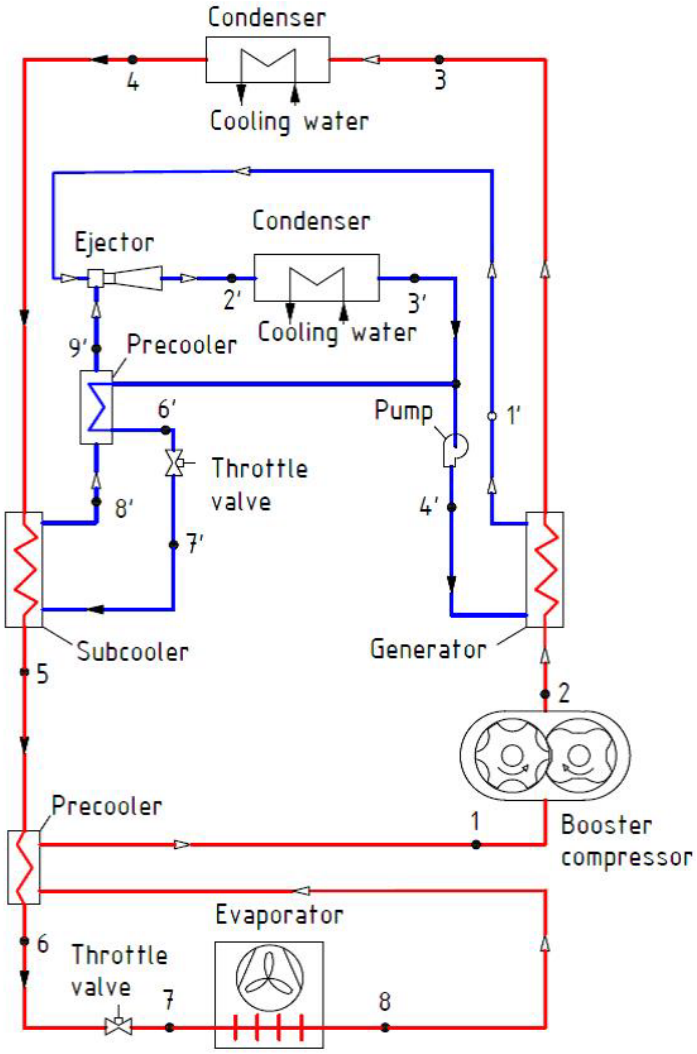


Figure 1: Combined CER system

2. SYSTEM ANALYSIS OF THE COMBINED COMPRESSION-EJECTOR REFRIGERATION SYSTEM

A system analysis of the combined compression-ejector refrigeration system is carried out in the present study. Governing equations based on the first and the second law of thermodynamics are established.for every component of the CCER system.

2.1. Governing equations of the components in Combine Compression-Ejector Refrigeration System.

2.1.1. Generator

In the generator, the refrigerant in the ER system undergoes a phase-change process (evaporation), while the refrigerant in the VCR system undergoes a cooling process in vapor state. The generator functions as a heat exchanger similar to an evaporator. The temperature difference at the neck point of the generator is denoted as ΔTNG, which is a predetermined design parameter. Referring to the state at the neck point as state 02 for the VCR system refrigerant vapor and as state 01' for the ER system, we derive the following governing equations:

$$T_{02} = T_g = \Delta T_{NG} \tag{1}$$

$$m_e \left(h_{02} - h_3\right) = m'_e \left(h'_{01} - h'_4\right). \tag{2}$$

where $h_{02} = h_g\left(T_{02}, P_c\right); h_2 = h_g\left(T_2, P_c\right); h'_{01} = h_f\left(T'_{01}\right);$ (3)

$$T'_{01} = T_g \tag{4}$$

$$T_4' = T_3' = T_c' ; \tag{5}$$
$$h_4' = h_{01}' - c_p' \left(T_{01}' - T_4' \right) = h_{01}' - c_p' \left(T_g' - T_c' \right) \tag{6}$$
$$m_e \left(h_2 - h_{02} \right) = m_e' \left(h_1' - h_{01}' \right) ; \tag{7}$$
$$Q_g = Q_g' = m_e \left(h_2 - h_3 \right) = m_e' \left(h_1' - h_4' \right) . \tag{8}$$

2.1.2. Ejector

The ejector plays a critical role in ejector-enhanced refrigeration cycles, and its performance directly influences the system's efficiency and energy performance. In [12-15], the fundamental concepts of the constant-pressure mixing technique were proposed. It was hypothesised that the primary and secondary streams would blend in a chamber with uniform, constant pressure. As depicted in Figure 2, the mixing chamber is located between sections 1 and 2, where the pressure is assumed to be consistent. If the flow, after complete mixing, attains supersonic velocity ($M_{m2} > 1$ or higher), a normal shock wave is anticipated in the constant-area chamber between sections 2 and 3. The static pressure of the mixed flow upon exiting section 3, at uniform subsonic velocity, increases in the diffuser.

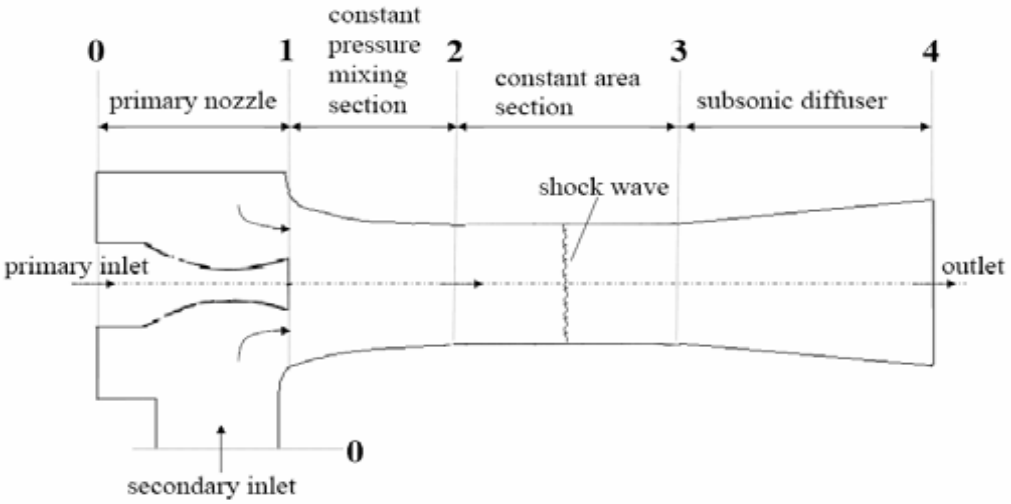


Figure 2: Constant-pressure ejector flow model

In the derivation of the constant-pressure mixing ejector model, the following assumptions are generally made: (1) The primary and secondary streams at the inlet of the ejector and the mixed flow at the exit of the ejector are at stagnation conditions. (2) Velocities are uniform at all sections. (3) Mixing of streams occurs at constant pressure between sections 1 and 2. (4) If the mixed flow is supersonic at section 2, a shock wave will occur between sections 2 and 3 and the flow is subsonic at section 3. The entrainment ratio is also an important parameter that describes the ER system's performance. This parameter is related to the cooling capacity and directly depends on the refrigeration type and ejector geometry. The entrainment ratio is the ratio between the mass flow rate of the secondary flow and the mass flow rate of the primary flow, given as:

$$U = \frac{m_e'}{m_p'} \tag{9}$$

where, m_e' and m_p' represent the flows of the low-boiling working fluid through the evaporator-air cooler (ejected low-boiling working fluid at low pressure) and the generator (low-boiling working fluid at high pressure), respectively.

2.1.3. ER Condenser

Assuming that the condensate at the exit of the condenser (point 3') in the ER is at a saturated-liquid state. The governing equations of the ER condenser are:

$$T_3' = T_c' \tag{10}$$
$$P_c' = P\left(T_c' \right) . \tag{11}$$
$$h_3' = h_{gs} \left(T_c' \right) \tag{12}$$
$$h_2' = h_{gs} \left(T_2', T_c' \right) \tag{13}$$
$$Q_c' = \left(m_p' - m_e' \right) \times \left(h_2' - h_3' \right) \tag{14}$$

2.1.4. ER precooler

The precooler in the ERM is a simple heat exchanger that can be characterized by the effectiveness:

$$\eta_{pc} = \frac{T_3' - T_6'}{T_3' - T_8'}; \tag{15}$$

η_{pc} is a designated parameter in the precooler design. Equation 15 can be employed to ascertain a temperature if the other two temperatures are known.

2.1.5. Subcooler

The subcooler is utilised to lower the temperature of the liquid condensate in the VCRS by harnessing the evaporation heat of the ER. Essentially, the subcooler functions akin to a heat exchanger, resembling an evaporator with the refrigerant in the ER undergoing an evaporation process. We assume that the thermodynamic state at the exit of the subcooler (state 8′) for the ERM is a saturated-vapour state, and the temperature difference at the neck point (state 7′) of the subcooler is denoted as $\triangle T_{\mathrm{NS}}$. $\triangle T_{\mathrm{NS}}$ is specified as the design parameter for the heat exchanger. Consequently, we derive the following governing equations:

$$T_8' = T_e' = T_7' \tag{16}$$
$$T_7 = T_7' + \triangle T_{\mathrm{NS}} \tag{17}$$
$$h_8' = h_{gs}\left(T_8'\right) \tag{18}$$
$$h_7' = h_6' \tag{19}$$
$$Q_e' = m_e'\left(h_8' - h_7'\right) \tag{20}$$
$$Q_e = m_e\left(h_4 - h_5\right) \tag{21}$$
$$Q_e' = Q_e = m_e'\left(h_8' - h_7'\right) = m_e\left(h_4 - h_5\right) \tag{22}$$

2.1.6. VCRS condenser

Assuming that the condenser of the *VCRM* has a degree of sub-cooling, $\triangle T_{SC}$, the governing equations are:

$$h_3 = h_g\left(P_c, T_3\right) \tag{23}$$
$$T_4 = T_c - \triangle T_{\mathrm{SC}} \tag{24}$$
$$h_4 = h_f\left(T_c\right) - c_p \triangle T_{SC} \tag{25}$$
$$Q_c = m_e\left(h_3 - h_4\right) \tag{26}$$

2.1.7. VCRS compressor

The compressor undergoes a non-isentropic process for vapor compression. The power input to the compressor can be represented by the following equation:

$$W_c = m_e\left(h_2 - h_1\right)/\eta_c\ . \tag{27}$$

where η_c is the compression efficiency, including the motor loss. The outlet temperature T_2 of the compressor can be determined by thermodynamic equation of state:

$$T_2 = f\left(h_2, P_c\right); \tag{28}$$

where

$$h_2 = h_1 + \left(h_{2s} - h_1\right)/\eta_s\ . \tag{29}$$

where η_s is the isentropic efficiency of the compression process.

$$h_{2s} = h_g\left(T_{2s}, P_c\right). \tag{30}$$
$$T_{2s} = h_g\left(P_c, s_2 = s_1\right); \tag{31}$$

3. RESULTS AND DISCUSSION

Utilising capability-driven design methodology for the development and deployment of energy efficiency projects enables the tracking of risks throughout the project lifecycle, thus aiding in their prevention and facilitating timely system maintenance. This, in turn, helps in saving operational costs and manpower.

Using the above governing equations, a system performance calculation based on the concept of information - flow diagram can be carried out. The information-flow diagram shows that there are three independent design variables for a CCER system, namely, the condensing temperature T_c and the evaporating temperature T_e of the single-stage refrigeration system, and the evaporating temperature T_e' of the ER system. Given T_c, T_e, T_e' and the performance maps of the ejector and the compressor, the system performance of a CCER system can be carried out.

In the present study, we use R22 as the working fluid in the vapor compression refrigeration system and R245fa as the working fluid in the ER system. Eq. (9) is used for ejector performance calculation in system analysis since R245fa is used in The basic refrigeration system uses a screw-type compressor *Stal R5 M* which is made by *ABB*.

The coefficient of performance of the combined compression-ejector refrigeration system, ***COP***, is determined by the following definition:

$$COP = \frac{Q_e}{W_c + W_{pump}}, \tag{32}$$

where W_{pump} is the pumping power consumed by the circulation pump in the ER system. For comparison, the coefficient of performance of the VCR system, COP_{basic}, is determined. COP_{basic} is defined as

$$COP_{basic} = \frac{Q_e}{W_c}. \tag{33}$$

The analytical results presented in Table 1 demonstrate that the COP of a CCER system surpasses that of a basic refrigeration system. It is evident that the enhancement of COP is more notable at higher condensing temperatures of the VCR system, Tc. For T_e = -40°C, the COP improvement by employing a CCER system can be as substantial as 19.3% at T_c = 45°C and T_e' = 20°C (the evaporating temperature of the ER system).

When the ejector refrigeration machine is integrated with the VCR system, the refrigeration system's performance could be assessed by calculating the COP improvement ratio as follows:

$$COP_{improv} = \frac{(COP - COP_{basic})}{COP_{basic}} \times 100\% \tag{34}$$

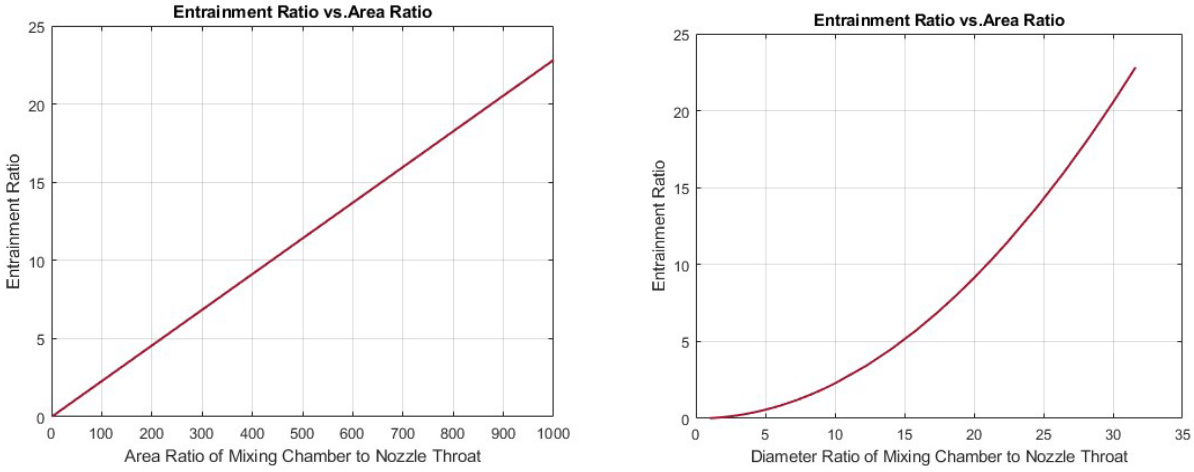
The greater the condensing temperature T_c, the greater the improvement in COP by employing a CCER system. This suggests that a CCER system might hold more importance for a refrigeration vessel in a VCR system utilising a water condenser device. Ejector performance is influenced by the temperatures of the primary stream and the secondary stream.

Table 1. Analytical results for COP of basic and CCER system at T_e= -40°C

R22 condensing temperature T_c (°C)	Basic system COP_{basic}	T_e'= 20°C		T_e'= 22°C		T_e'= 24°C	
		COP	COP_{improv} (%)	*COP*	COP_{improv} (%)	*COP*	COP_{improv} (%)
30	1,49	1,64	9,8	1,62	8,6	1,60	7,5
35	1,36	1,52	12,1	1,51	10,8	1,49	9,5
38	1,30	1,48	13,9	1,47	12,7	1,45	11,4
40	1,23	1,44	16,7	1,41	14,9	1,40	13,7
42	1,18	1,38	17,3	1,37	16,0	1,36	14,9
45	1,12	1,34	19,3	1,32	17,9	1,31	16,7

Figure 3(a) illustrates the effect of the temperature ratio of the secondary to primary streams on the ejector performance curve of entrainment ratio against area ratio.

Figure 3(b) depicts a similar curve, but the entrainment ratio is plotted against the diameter ratio instead of the area ratio for the sake of design convenience. Research on this ejector was carried out in calculated operating modes using a constant-pressure mixing ejector model in the temperature ranges of generation T_g=80°C, condensation T_c=30°C, and T_e'=20°C.



(a) **(b)**

Figure 3: Constant-area ejector:
(a)Entrainment ratio vs. Area ratio, (b) Constant-area ejector Entrainment ratio vs. Diameter ratio.

From Figure 3 (a,b), it is evident that the entrainment ratio is higher for the cooler secondary flow. In the small area/diameter ratio range, the temperature ratios do not have a significant influence on the ejector performance curve.

4. CONCLUSIONS

The research has facilitated the development of a theoretical framework for calculating, designing, and updating ship refrigeration units. This has addressed a range of scientific and practical issues pertinent to refrigeration technology, enabling further enhancement of machinery design and the judicious selection of optimal operational modes.

An examination of the global refrigerant market and its applicability to ship refrigeration systems in marine refrigerated transport. Analytical scrutiny has underscored the necessity to develop and refine models of ship refrigeration systems, focusing on improving energy efficiency and transitioning to environmentally sustainable refrigerants without requiring significant investment in system retrofitting;

Recognition of the pivotal role of maritime transport in the food supply cold chain, emphasising the significance of effective energy management for internal organisational communication and energy efficiency project implementation. An energy audit has led to a proposed programme aimed at enhancing energy efficiency and reducing environmental impact for refrigerated ship owners, proposing a transition from HCFC-22 to natural refrigerants in line with international environmental protocols;

The transition presents shipowners with the potential to achieve energy efficiency gains of 20-26%, along with reduced fuel consumption, through the modernisation of marine refrigeration systems;

Introduction of the concept of a combined compression-ejector refrigeration system for refrigeration vessels, leveraging waste heat from the basic refrigeration system to drive the ejector refrigeration system. This innovation is expected to enhance the coefficient of performance (COP) of the combined system, with simulation results confirming its viability and potential COP improvement of about 19%;

Exploration of ejector refrigeration (ER) systems for various applications, with heat capacities ranging from 5-100 kW, utilising heat from diverse energy sources such as condensation heat. These systems are characterised by their simple, reliable, and safe operation, along with low capital and operating costs, making them suitable for automation and meeting modern energy, environmental, and economic performance standards, thereby enabling competitiveness in the global refrigeration market and facilitating widespread exportation.

NOMENCLATURE

T	temperature (°C)	m	mass flow rate (kg/s)
h	enthalpy (kJ/kg)	Q	heat flux (kW)
IMO	International Maritime Organization	CII	Carbon Intensity Indicator
EEXI	Energy Efficiency Existing Ship Index	*COP*	Coefficient of Performance
VCRS	Vapor Compression Refrigeration System	ER	Ejector Refrigeration
CCRS	Combined Cycle Refrigeration System	CCER	Combined Compression Ejector Refrigeration

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