

ХОЛОДИЛЬНА ТЕХНІКА ТА ЕНЕРГОТЕХНОЛОГІЇ

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Modern refrigeration solutions for maritime sector and marine refrigeration transport

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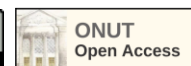
New coming environmental regulations from International Maritime Organization put each involved actor from ship manager, ship owner to cargo owner into a hard situation for a short time period to change the data collection process, to determine gaps considering operating needs, to create an improvement plan according to specific requirements, needs, and goals. It is one more signal, in order to reach the sustainability goal, the industry digitalization process, and available efficient and effective use of technologies should be pushed forward. From cold chain digitalization, refrigeration system maintenance, and retrofitting processes, in particular, data science, process science, and data mining can be used. Refrigeration system retrofitting process modelling is presented by data mining technology. A lack of knowledge and investment in cold chain best practices and infrastructure lead to projects failing. Efficient, controlled, and smart Refrigeration is a challenge for the sustainable refrigeration sector. The global reefer transport market will expand up to 6% from 2020 to 2027 and it is vital for countries involved in military operations as well. The results of energy, exergy, and exergoeconomic analysis of different solutions intended for marine refrigeration transport, the cascade refrigeration system with R717-R744 refrigerants is presented. It was found that the optimum condensation temperature for the refrigerant of the high-temperature circuit is 40 °C, while the boiling temperature of the lower-temperature circuit is -50 °C. The temperature mode can be considered optimal ceteris paribus. The article provides an analysis of ejector refrigeration systems that can be used to improve the energy performance of marine refrigeration plants. It is a recommended issue to consider not only industrial requests but policies, and regulations in the force and in projects development status that can change an organization's vision and aims of a strategic packet in own turn it can be affected a project budget change for labs, research institutions, shipyards.

Keywords: Maritime sector; Smart Refrigeration; Refrigerated Transport; Energy Efficiency; Exergy; Sustainability

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1. Introduction

Modern refrigeration solutions direct to smart refrigeration which is an actual problem for industry decarbonization and environmental impact reduction. Not only smart but efficient technology deployment

for refrigeration systems is crucial. The maritime sector is under the strong influence of the International Maritime Organization (IMO) environmental regulations discussed in [1]. Due to the last day's discussions within maritime organizations from the ship manager, ship owner, and ship operator up to the car-

go owner, each of them has a clear understanding that emissions performance is a vital factor for the business to be successful. New requirements put essential emission taxation that leads to value chain needs precise data as well as control over the emissions performance process. Current data reports are not satisfactory due to stakeholder expectations in order to be competitive within the IMO regulations framework. Not much time left to change the situation occurred for small and medium business owners who have old ships in charge.

To make any changes within the maritime sector need to start from the cold chain itself for the digitalization process deployment through the sea transport system, ship owners up to the ship itself, and operated onboard systems in particular.

The cold chain is the process that helps clients to keep perishable products at the required temperature and humidity properties to ensure product safety and quality. Transportation, as well as storage, are the two areas that move the chain forward. The vital issues for the cold chain are time and temperature, these issues force organizations to integrate the optimal available technologies to meet the challenges that they have been faced with. The control of activities along with the achievement of goals, will improve the performance of organizations. According to research, the global cold chain market size is proposed to expand at a compound annual growth rate (CAGR) of 18.6% from 2023 to 2030 [2]. The global reefer transport market will expand up to 6% from 2020 to 2027, this is forcing research teams to put efforts into the development of new technologies and new implementation approaches for reefer transport [3].

In order to move forward in the refrigeration sector, one may argue that it could be appropriate to make use of the experiences that the energy sector has had. Communication technologies and machine learning could be used for the digitalization of the refrigeration sector and the cold chain in particular.

Due to innovation and disruption accelerates organizations are obliged to quickly digitalize and become data-driven. Smart and controlled refrigeration can be represented by the domain-specific big data integration platform, empowering the digital data to create sustainable value and adapt quickly to changing requirements and opportunities in the market.

The new generation of edge technologies in refrigeration is not about 'just making it happen'. The cold chain must transform internally to winner innovations and embrace a startup approach throughout

the entire organization. That starts with adopting digital DNA [4].

With today's cold chain and its areas evolving towards the distributed Internet-of-Things (or Cloud), so does the refrigeration infrastructure have to evolve too. Exponential volumes of data should be crunched, processed faster, and shared across the system and network boundaries to create insight and action in real-time. An information management infrastructure is required to realize the true benefits of edge digital cold chain technologies. This information management infrastructure must be secure, reliable, elastic, scalable, high-performant, flexible, and cost-effective.

The Institute of Electrical and Electronics Engineers presented the Process Mining Manifesto [5] to support the adoption of process mining to redesign business operations in any industry. While proponents of process mining, like the IEEE, promote its adoption, Gartner notes that market factors will also play a role in its acceleration. Digitalization industry efforts will speed up study around processes, and process mining, next increasing the deployment rate of novel technologies, such as artificial intelligence, task automation, and hyper-automation. The pace of these organizational changes will also require businesses to apply operational resilience to adapt as well. As a result, enterprises will increasingly lean on process mining tools to achieve their business outcomes. Process mining is founded on the cross sections of data science (artificial intelligence, machine learning, statistics, advanced analytics, data management, data warehouse, data lake, business intelligence, etc.) and process science (simulation, operations research, business process management, industrial engineering, process modelling, planning and control, etc).

Using a data mining approach for industry digitalization now it is possible to get comprehensive sets of publicly available benchmarks, to get a better understanding from the experts in the area in the different quality criteria. Choosing between 40 commercial process mining tools, it is easier nowadays to apply process mining, to understand the diagnostics. Due to the provided many approaches which combine process mining and machine learning, there has been major progress in improving understanding for newcomers.

alignFor energy system analyses, exergy analysis is commonly accepted as a useful tool in obtaining an understanding of the overall system itself and system components due to quantifying inefficiency sources as well as distinguishing energy quality in [6-12]. Exergy with energy assessment can help in taking an effective

engineering decision for the required steps concerning system improvement.

2. Main section

To digitalize the cold chain, refrigeration system maintenance, and retrofitting process in particular it is proposed to use data mining. As process mining can be used in any industry including manufacturing, and maintenance, procurement and sales, education and consulting, logistics and etc., the refrigeration sector can be opened for process mining as well. If there is a need to advance operational processes it is possible to perform it using systematically the event data as well as by combining event data and process models (Petri Net, BPMN, UML) with PM techniques: to identify bottlenecks and deviations, to prognosis and analyze system performance problems and compliance them, to maintenance the automation or can be repetitive activities removal. Any process which requires repeated execution of activities in order to deliver products or services is a focus for process mining realization. Refrigeration system retrofitting process modeling can be presented by data mining.

2.1 General refrigeration system retrofitting process modeling by data mining.

It is better to use drop-in refrigerants. The phasing-out of Ozone-Depleting Substances, and in particular, Chlorofluorocarbons in the refrigeration sector, has resulted in new refrigerants development that are

often claimed to be direct replacements for the original Ozone-Depleting Substances. Particular refrigerants differ in composition; such as synthetic fluorocarbons, hydrocarbons, natural refrigerants, or single substances, also blends. Still, it is significant to carefully study any specific refrigerant that is being considered for the refrigeration system used, to ensure that it is an appropriate replacement for the special conditions and that those working with the refrigerant are fully aware of its implications.

The following should be carried out: Material Safety Data Sheets checking in order to comprehend its safety characteristics, relevant information request, related to the refrigerant from the refrigerant manufacturer, finding out whether or not the mineral oil needs to be replaced or not, looking for training on the proper handling of these new refrigerants for technicians.

There are many notations to describe processes, ranging from Petri Nets, Business Process Modelling and Notations (BPMN), Unified Modelling Language, Directly-Follows Graphs and etc. Consider a refrigeration system retrofitting process involving the following activities.

A generalized procedure is proposed to be followed when retrofitting any refrigeration system with an alternative refrigerant. It is clear, that may occur specific differences due to the certain characteristics of the refrigeration system (RS) under consideration and the refrigerants involved. The BPMN (see Fig. 1) and Petri Net (see Fig. 2) models provide a view of how this flow works for the retrofitting of HCFC refrigeration equipment.

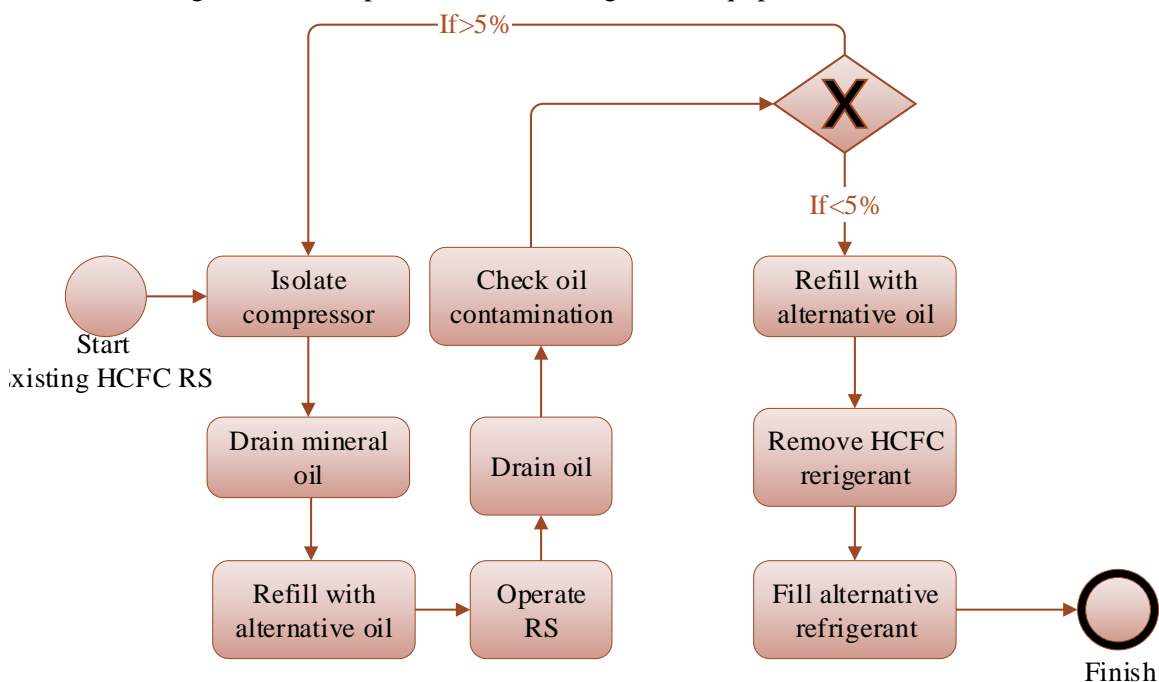


Figure 1 – BPMN modeling for retrofitting process

The procedures to perform this retrofitting are explained below. It is significant to follow the refrigerant manufacturer's guidelines for RS retrofitting. For example, the RS retrofit to hydrocarbons must be executed taking into consideration safety aspects.

Fig. 1 shows the RS retrofitting process model by BPMN. The process starts with the activity to isolate the compressor followed by the activity to drain mineral oil (drain and recover the existing mineral oil charge, measure the quantity, and compare with the recommended oil charge to determine the quantity of oil left in the system.), to refill with alternative oil (charge the system with new and correct amount of alternative refrigerant oil as recommended by compressor/system manufacturer.), to operate the refrigeration system (run the system while performing the oil change procedure as many times as necessary until the

mineral oil in the system does not exceed the recommended 5% acceptable level.), to drain oil, to check oil contamination than following exclusive choice if oil contaminant more than recommended 5% - return to activity to isolate the compressor if oil contaminant less than 5% - continue with the activity to refill with alternative oil, to remove HCFC refrigerant and complete with activity to fill RS with alternative refrigerant (charge the RS with the appropriate amount of alternative refrigerant. This can normally be approximated by using the ratio of liquid densities at the condensing temperature. When charging the system with alternative refrigerant, use the same charging that you would use for HCFC refrigerant to ensure optimal system performance.

The BPMN RS retrofitting process starts with a start event (shown as a circle) and ends with an end event (shown as a thick circle).

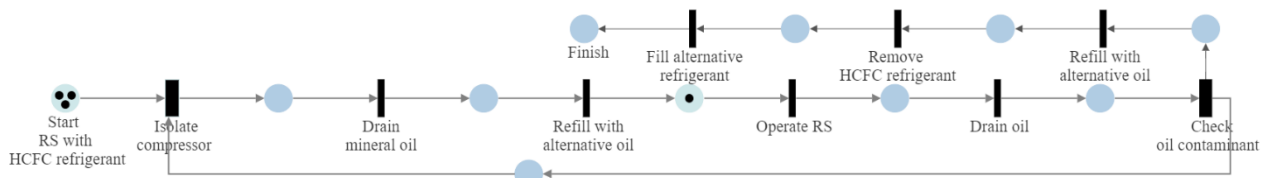


Figure 2 – Petri Net modeling for RS retrofitting process

Fig.2 models the same RS retrofitting process but in terms of a Petri Net. The circles correspond to places (to states) and the rectangles correspond to transitions (to activities) that occur in the RS retrofitting process model. Places may hold tokens, or may not. A place is called marked if it contains a token (the black dot). A marking is a distribution of tokens over places. A transition is enabled if all input places are marked. Although the behavior of the Petri net in Fig.1 is the same as the BPMN model in Fig.2, it is easier to refer to the states of the process model.

2.2. Exergy and energy analysis

The transportation component of the cold chain has been studied in order to meet not only energy efficiency issues but environmental regulations as well.

Concerning sea refrigerated transport; it is proposed to perform an exergy analysis. Exergy analysis shows itself as a great tool for the work potential assessment of the inlet and outlet material and heat streams as well as for the location and magnitude of irreversibility loss derivation. This analysis presents vital data concerning the total irreversibility distribu-

tion of the system among the components, determining which component weighs more on the overall system inefficiency.

The total exergy of the system [13] can be presented as physical exergy, kinetic exergy, potential exergy, and chemical exergy is presented in

$$\dot{E}_{X,total} = \dot{E}_{X,physical} + \dot{E}_{X,kinetic} + \dot{E}_{X,potencial} + \dot{E}_{X,chemical} \quad (1)$$

The kinetic, potential, and chemical exergy are considered insignificant in this study. The physical exergy is considered in the system. The physical exergy is obtained from the thermal and mechanical processes as shown in

$$\dot{E}_{X,physical} = \left(\dot{m} \cdot \left[(h_i - h_0) - T_0 (s_i - s_0) \right] \right), \quad (2)$$

where m – the mass flowrate; s – the specific entropy at the condition specified for the species; subscript 0 represents environment conditions.

The general exergy balance as shown in

$$\dot{E}_{X,D} = \dot{E}_{X,in} - \dot{E}_{X,out} \quad (3)$$

By considering Eq. (3), the exergy destruction rate in each component of the Vapor Compression Refrigeration System (VCRS) is obtained as shown below. The exergy destruction of the compressor is presented in

$$\dot{E}_{X,D \text{ comp}} = \dot{E}_{X,1} - \dot{E}_{X,2} + \dot{W}_{el}. \quad (4)$$

The exergy destruction of the condenser is shown

$$\dot{E}_{X,D \text{ cond}} = \dot{E}_{X,2} - \dot{E}_{X,3} - \dot{E}_{X, \dot{Q}_{\text{cond}}}. \quad (5)$$

The exergy destruction of the subcooling is presented

$$\dot{E}_{X,D \text{ sub}} = \dot{E}_{X,3} - \dot{E}_{X,4} + \dot{E}_{X, \dot{Q}_{\text{sub}}}. \quad (6)$$

Regarding the expansion valve, a throttling process as shown

$$\dot{E}_{X,D \text{ exp}} = \dot{E}_{X,4} - \dot{E}_{X,5}. \quad (7)$$

The exergy destruction of the evaporator is presented

$$\dot{E}_{X,D \text{ eva}} = \dot{E}_{X,5} - \dot{E}_{X,6} + \dot{E}_{X, \dot{Q}_{\text{eva}}}, \quad (8)$$

where $\dot{E}_{X, \dot{Q}_{\text{eva}}}$ – the thermal exergy rate related with

\dot{Q}_{eva} as shown in

$$\dot{E}_{X, \dot{Q}_{\text{eva}}} = \dot{Q}_{\text{eva}} \cdot [(T_{cs} - T_0) / T_{cs}]. \quad (9)$$

The exergy destruction of the superheating is presented

$$\dot{E}_{X,D \text{ sup}} = \dot{E}_{X,6} - \dot{E}_{X,1} + \dot{E}_{X, \dot{Q}_{\text{sup}}}. \quad (10)$$

The subscripts used in the above exergy balance equations *comp*, *cond*, *sub*, *exp*, *eva* and *sup* indicate compressor, condenser, subcooler, expansion valve, evaporator and superheater respectively. Using Eq. (4)-(10), the total exergy destruction of the VCRS as shown

$$\begin{aligned} \dot{E}_{X,D \text{ total}} = & \dot{E}_{X,D \text{ comp}} + \dot{E}_{X,D \text{ cond}} + \dot{E}_{X,D \text{ sub}} + \\ & + \dot{E}_{X,D \text{ exp}} + \dot{E}_{X,D \text{ eva}} + \dot{E}_{X,D \text{ sup}}. \end{aligned} \quad (11)$$

The energy [14] 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). 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 Fig. 2, for the two-stage VCRS results present 39% reduction in exergy.

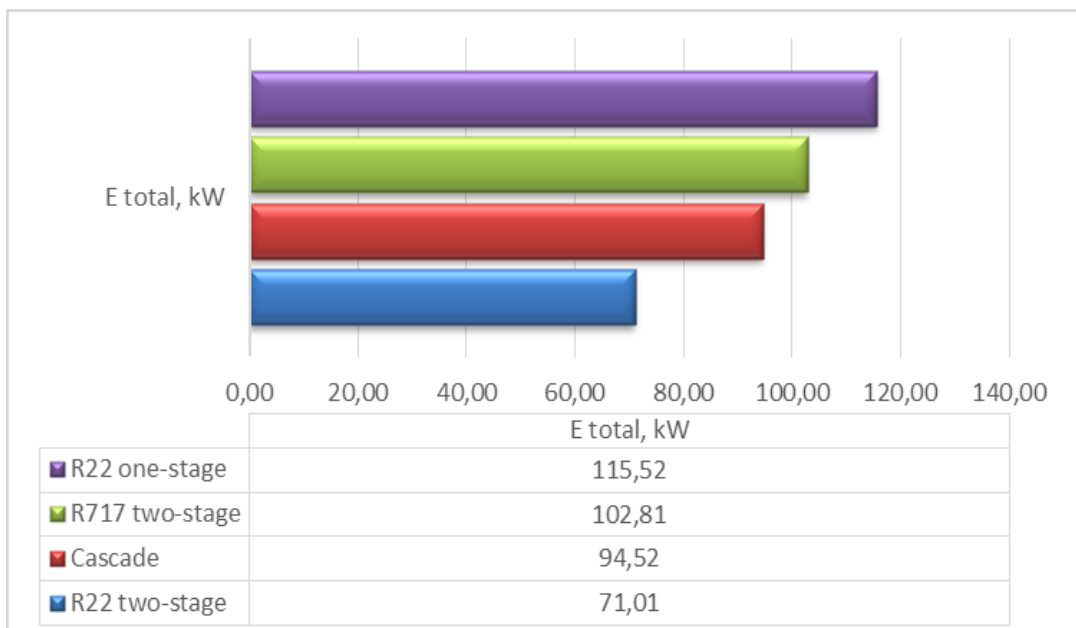


Figure 3 – Total exergy destruction of VCRS

As it can be seen from Fig.3, the cascade refrigeration system with R717-R744 refrigerants can be an alternative to R22 due to its slightly lower COP value

[14]. Fig. 4 shows data according to variable sea water temperatures and also COP_{carnot} , COP_{theor} , and degree of thermodynamic perfection values.

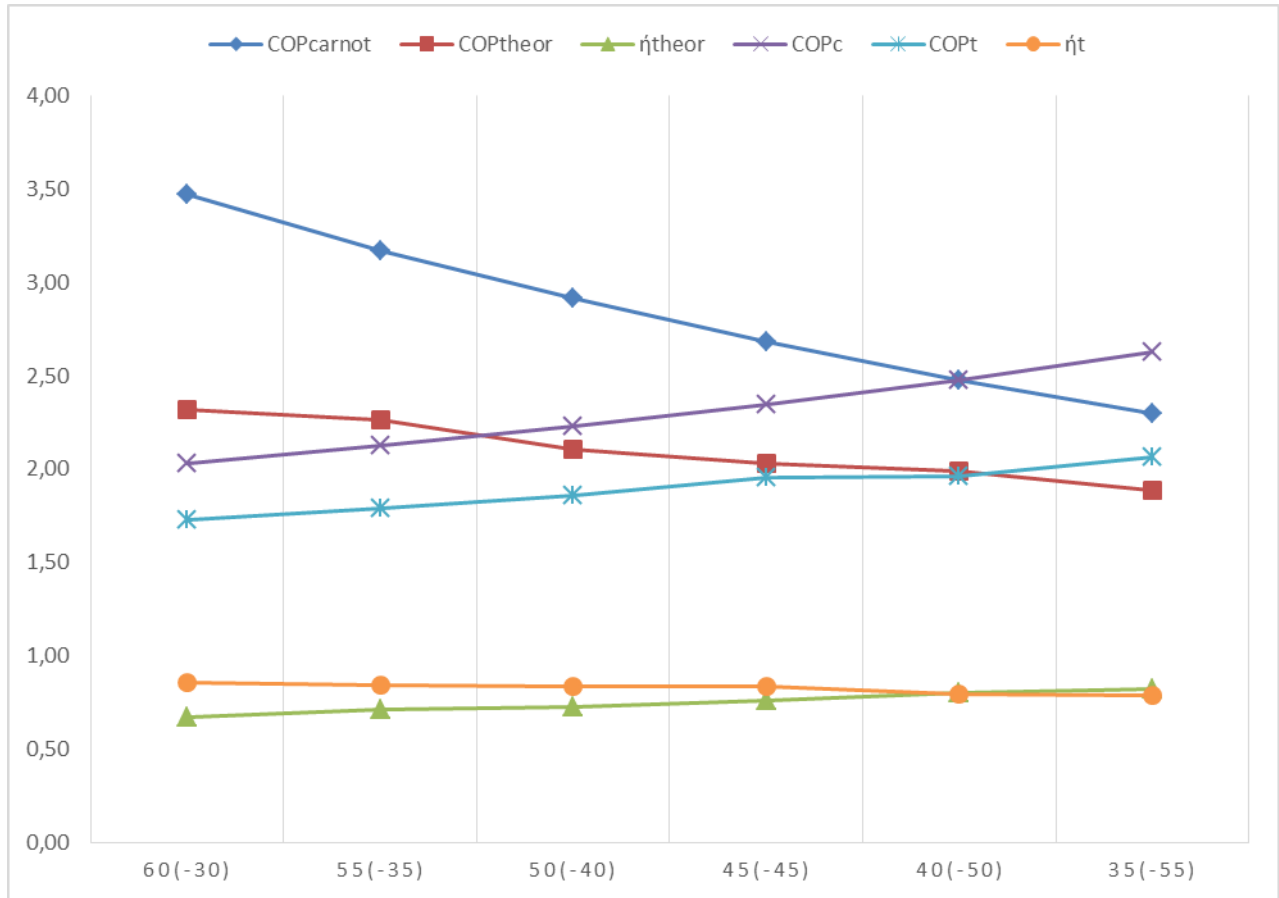


Figure 4 – Optimum condensing (boiling) temperature of a cascade refrigeration system with R717-R744 refrigerants

Therefore, the analyses have been carried out using R717-R744 refrigerants. It is clear from Fig. 3 that when the sea water temperature increases, the compressor outlet pressure increases in order to ensure condensation at the condenser outlet. When the compressor output pressure increases, the power requirement of the compressor increases, and this reduces the COP value of the system. This study, it is aimed to reduce the exergy destruction of VCRS of a ship by considering the complementary additional compressor and transition from single-stage to two-stage compression of VCRS. First, exergy and the second law efficiency analyses of VCRS have been discussed in the case of variable single-stage to two-stage compression and different refrigerants. The results of energy, exergy, and exergoeconomic analysis of different solutions intended for marine refrigeration transport, the cascade refrigeration system with R717-R744 refrigerants is presented. It was found that the optimal condensation temperature for the refrigerant

of the high-temperature circuit is 40 °C, while the evaporation temperature of the lower-temperature circuit is -50 °C. The temperature mode can be considered optimal *ceteris paribus*. The economic assessment of a cascade refrigeration system operating on a pair of carbon dioxide - ammonia refrigerants show its economic efficiency, compared to the same system which works with other refrigerants, in the amount of 3.8% of total capital costs. The feasibility of its development is argued by the minimal impact on the environment.

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 [14].

One of the ways to improve energy consumption for existing and new ships is to recover the heat of exhaust gases from the main and auxiliary engines,

which is relevant in connection with the new provisions on energy efficiency and the topic of greenhouse gases.

Heat losses with exhaust gases for a marine power plant can reach from 30% to 50% or more, depending on the type of installation and operating conditions. A comparative analysis of various refrigerating

machines shows that the most promising for ship air conditioning and refrigeration systems are heat-using ejector refrigerating machines (ECM) using low-boiling working substances in [15-20].

Marine ERSs are structured and divided into 5 sub-sections that cover all major ejector refrigeration technologies presented in the literature (Fig. 5).

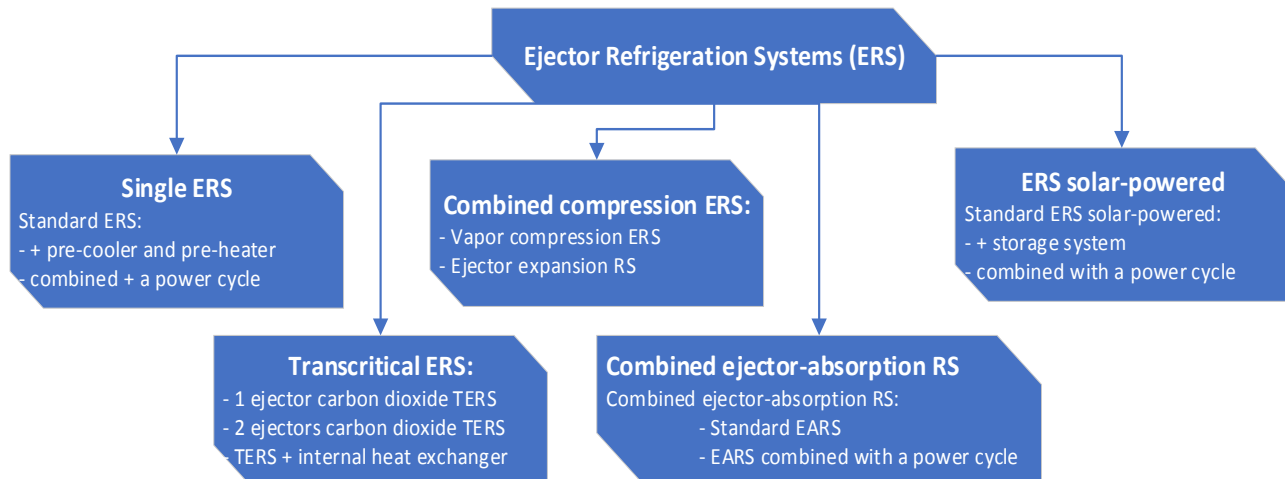


Figure 5 – Overview of marine ejector refrigeration systems

Presented in Fig. 5 the Combined Compression-Ejector Refrigeration System is a relatively new and promising approach to creating energy-efficient and reliable cooling systems for ships.

The results of numerous studies have shown that ERS has a number of advantages when used on ships as part of refrigeration units, such as:

1. Do not require internal combustion engines or electricity to operate them. This means that they do not depend on the availability of fuel or electrical power on the ship, which can be important on long sea voyages.

2. It can be used various energy sources for its operation, including solar panels and other devices. This allows you to choose the most efficient and economical source of energy for the operation of the refrigeration unit.

3. It has high reliability and durability due to the absence of moving parts. This reduces the likelihood of breakdowns and maintenance requirements.

4. Enable high-efficiency cold production, resulting in fuel savings and lower operating costs.

5. Can be easily integrated into an existing marine refrigeration plant, which provides automation of the refrigeration process and simplifies the work of operators.

All in all, ejector chillers are a reliable, efficient, and economical solution for marine refrigeration.

3. Conclusions

Sustainability changes industries and the maritime sector as well. Innovation technologies, advanced analytics and industry digitization, electrification and process efficiencies, decarbonization operations and systems, are supporting the global economy make it able to reach sustainable goals. In order to be competitive, with opportunities to play in the global market ship owner organizations must bring changes into. Emission data should represent where efficient and effective data collection and processing are critical. New coming IMO regulatory requirements are resulting in reporting needs increasing and new ways of data use. Existing data streams do not respond to new requests from stakeholders. Fuel consumption is a main input factor that is monitored, collected, and stored by various techniques with manual undertaking and digital. The data processing and data sharing perform in different ways, by different ships and organizations, producing errors. Using data science, process science, and process mining can be an option for confidence in your data, reducing time in data presentation, and making sure that this data suits stockholder and organization purpose, it is reusable and provide new potential.

Refrigeration system retrofitting process modeling by process mining is presented as one more option

for data processing, controlling, and ensuring in required quality for the data stream.

The Cold Chain business should focus on getting new opportunities together with customer requirements satisfaction. In order to develop programs that are intended to manage the climate, to manage sustainability, and to manage and control energy efficiency, a set of activities should be done.

It is proposed to put attention on the leading-edge issues for each component of the cold chain: cold storage, transport, and systems. To be able to meet requests, experts must explicit their own knowledge base and learn about the technologies available in order to achieve sustainability goals.

Cross-sectoral issues should be taken into consideration as well. It is a policy and new coming regulations, economy within rates and costs, technology to make the step to the digitalization, smart refrigeration and controlling, legal issues concerning employment, trade, safety, and environment within sustainability, decarbonization, and recycling issues.

Reefer freight improvements and refrigeration systems improvements for fishing carriers contribute to sustainability throughout the refrigeration sector. The vapor compression systems are leading in the refrigeration sector for preserving frozen and chilled food products. This technology is used for the efficient refrigeration of products that need to be supplied in chilled or frozen form. Growing demand for these products in developing nations and the awareness about perishable food products is making a demand for chilled and frozen food products.

The fast-growing need for refrigerated transport and cold storage will increase competitiveness for organizations in the broader market. The future market leader is an organization that can offer efficient smart and controlled refrigeration for customers. Nowadays, refrigeration systems retrofitting oftentimes takes a leading role in energy efficiency projects. Small and medium businesses within the refrigeration sector attract more attention for distribution within markets for using each opportunity to small-scale refrigeration facilities and lightweight refrigerated transport. Ensuring the cold chain meets organization, policy, and client requirements is a vital issue to the preservation as well as for the growth of not only the global economy but also human well-being.

Utilization of the low-potential heat of the exhaust gases leaving the main and auxiliary engines in the ejector refrigeration system can provide significant savings in fuel and electricity for the ship's power

plant, which in turn contributes to the protection of the environment from pollution.

Therefore, it is of great interest to conduct further research with the aim of creating a marine refrigeration system that meets modern requirements in terms of energy, economic and environmental indicators and is competitive in the global market of refrigeration units.

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Хмельнюк М.Г.: перевірка, формальний аналіз, написання – огляд та редагування відповідно до паспорту спеціальності та адміністрування. **Ялама В.В.:** моделювання процесу модернізації холодильної системи шляхом аналізу ексергетичних та енергетичних даних, аналіз характерних особливостей конструктивного виконання електронних холодильних систем. **Яковлева О.Ю.:** візуалізація, програмне забезпечення. **Трандафілов В.В.:** формальний аналіз, верифікація.

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Сучасні холодильні рішення для морського сектору та морського холодильного транспорту

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Нові екологічні норми Міжнародної морської організації ставлять кожного учасника процесу - від судноводія, судновласника до вантажовласника - перед необхідністю змінити процес збору даних,

визначити групи з урахуванням операційних потреб, розробити план вдосконалення відповідно до конкретних вимог, потреб і цілей. Це ще один сигнал, що для досягнення мети сталого розвитку необхідно прискорити процес діджиталізації галузі та реалізації доступних ефективних технологій. У процесах діджиталізації холодильного ланцюга, експлуатації та модернізації холодильних систем можна використовувати, зокрема, науку про дані, науку про процеси та інтелектуальний аналіз даних. Моделювання процесу модернізації холодильної системи представлено технологією інтелектуального аналізу даних. Брак знань та інвестицій у найкращі практики та інфраструктуру холодового ланцюга призводить до провалу проєктів. Ефективне, контрольоване та розумне охолодження - це виклик для сектору сталого охолодження. Світовий ринок рефрижераторних перевезень зростає на 6% з 2020 по 2027 рік, і він є життєво важливим для країн, що беруть участь у військових операціях. Представлено результати енергетичного, ексергетичного та ексергоекономічного аналізу різних рішень, призначених для морського рефрижераторного транспорту, каскадної холодильної системи з холодоагентами R717-R744. Встановлено, що оптимальна температура конденсації холодоагенту верхнього каскаду становить 40 °C, а температура кипіння нижнього каскаду -50 °C. Температурний режим можна вважати оптимальним за інших рівних умов. У статті наведено аналіз ежекторних холодильних систем, які можуть бути використані для покращення енергетичних характеристик суднових холодильних установок. Рекомендується враховувати не лише промислові запити, але й політику та нормативно-правові акти, що діють та перебувають на стадії розробки проєктів, які можуть змінити бачення організації та цілі стратегічного пакету, що, в свою чергу, може вплинути на зміну бюджету проєкту для лабораторій, науково-дослідних інститутів, верфі.

Ключові слова: Морський сектор; Розумне охолодження; Рефрижераторний транспорт; Енергоефективність; Ексергія; Сталый розвиток

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