UDC 621.43.056:632.15 **DOI https://doi.org/10.33082/td.2024.1-20.06**

THE IMPACT OF HEAT-EXCHANGERS SURFACE FOULING AND THE POSSIBILITIES OF THEIR CLEANING

V.I. Kholdenko
Senior Lecturer,
Odessa National Maritime University, Odesa, Ukraine,
ORCID ID: 0000-0003-0071-7055

Summary

Introduction*: This study investigates the real-world effects of pollutants on ship heat exchangers in the marine sector, focusing on the complex issues influencing maintenance expenses, environmental sustainability, and operational effectiveness. The core of the issue is figuring out a long-term, practical way to lessen the damage that heat-exchangers surface heat-exchangers surface fouling causes to ship heat exchangers****. Purpose.*** *The article aims to investigate and evaluate how pollutants affect ship heat exchangers in the marine sector from a practical standpoint. It seeks to shed light on how pollutants, such as chemicals, debris, and oil residues, impact a vessel's environmental sustainability, maintenance costs, and operational effectiveness. The essay analyzes the complex issues caused by surface fouling-induced damage, highlighting the dangers of decreased thermal conductivity, greater overheating, higher maintenance costs, longer downtime, and possible environmental effects.* ***Result.*** *One practical consequence of pollutant-induced damage is that it calls for substantial and frequent cleaning, repairs, and maybe replacements of the heat exchanger components, which raises maintenance costs. Traditional cleaning procedures involve prolonged downtime for manual intervention, which worsens the economic effects on shipping businesses and trade routes. Furthermore, the study highlights the negative effects uncontrolled pollutants have on the environment, highlighting how crucial regulatory compliance is to avoiding legal ramifications and preserving the good name of the sector.* ***Conclusion.*** *In conclusion, preserving marine operational effectiveness and environmental sustainability requires reducing the impact of pollutants on ship heat exchangers. The selection of particular heat exchanger types requires customized cleaning techniques. Advanced solutions are provided by ecologically safe chemical agents, high-pressure water jets, and automated robotic systems. To avoid losing efficiency, regular cleaning must be done under the direction of real-time monitoring. Maintaining heat exchanger performance and guaranteeing the lifespan of ship power plants in the face of changing surface fouling concerns requires striking a compromise between operational needs, environmental responsibility, and proactive maintenance.*

Key words: *Ship Heat Exchangers, Heat-exchangers surface heat-exchangers surface fouling Impact, Operational Efficiency, Maintenance Costs, Environmental Sustainability.*

ВПЛИВ ЗАБРУДНЕННЯ НА РОБОТУ СУДНОВИХ ТЕПЛООБМІННИКІВ І МОЖЛИВОСТІ ЇХ ОЧИЩЕННЯ

В.І. Холденко
доцент,
Одеський національний морський університет, Одеса, Україна,
ORCID ID: 0000-0003-0071-7055

Анотація

Вступ. *Це дослідження присвячене вивченню реального впливу забруднюючих речовин на суднові теплообмінники в морському секторі. Автор зосереджується на складних питаннях, що впливають на витрати на технічне обслуговування, екологічну стійкість і експлуатаційну ефективність. Суть проблеми полягає в тому, щоб знайти довгостроковий і практичний спосіб зменшити шкоду, яку забруднення завдає судновим теплообмінникам.* ***Мета.*** *Забруднюючі речовини знижують теплопровідність і експлуатаційну ефективність шляхом утворення ізоляційних шарів на поверхнях теплообмінників з бруду, хімікатів і залишків нафти. Отже, існує пряма загроза надійності судна через підвищену ймовірність перегріву двигуна, що підкреслює критичну необхідність застосування методів зменшення забруднення.* ***Результат.*** *Одним з практичних наслідків пошкоджень, спричинених забруднюючими речовинами, є необхідність значного і частого очищення, ремонту і, можливо, заміни компонентів теплообмінника, що підвищує витрати на технічне обслуговування. Традиційні процедури очищення передбачають тривалі простої для ручного втручання, що погіршує економічні наслідки для судноплавних компаній і торговельних шляхів. Крім того, у дослідженні підкреслюється негативний вплив неконтрольованих забруднювачів на навколишнє середовище, тому важливим є дотримання нормативних вимог для уникнення юридичних наслідків і збереження доброго імені галузі.* ***Висновок.*** *Для подолання цих реальних наслідків необхідна комплексна стратегія, що включає передові технології очищення, проактивні процедури технічного обслуговування та дотримання екологічного законодавства. Таким чином, морський сектор може зменшити небезпеку для економіки, безпеки та довкілля, пов'язану з впливом забруднюючих речовин на суднові теплообмінники, зберігаючи при цьому надійність і ефективність експлуатації суден навіть перед обличчям мінливих загроз.*

Ключові слова: *суднові теплообмінники, вплив забруднення, експлуатаційна ефективність, витрати на технічне обслуговування, екологічна стійкість.*

Introduction. The maritime sector is essential to international trade because it makes it easier to move products across large oceans. The heat-exchangers surface fouling as well as its far-reaching effects provide a serious issue for this vital industry. Heat-exchangers surface fouling's impact on ship heat exchange systems has become one of the most important environmental challenges impacting marine operations. For maritime operations, the surface fouling of ship heat exchanger surfaces presents an important threat to the environment. In addition to reducing internal power plant efficiency, it raises fuel consumption and emissions, which degrades the quality of the air and water. If pollutants and debris are spilled during cleaning, marine ecosystems may suffer. Financial penalties for breaking environmental standards highlight the industry's accountability. Reducing heat exchanger surface fouling is in line with more general environmental sustainability objectives, which acknowledge the marine industry's contribution to reducing its ecological impact worldwide. Ship heat exchangers are crucial parts of a vessel's cooling and propulsion systems, and the entire performance of marine engines depends on their operating efficiency [7].

The persistent growth in maritime heat-exchangers surface fouling, resulting from diverse human activities, has presented a range of difficulties for ship operators. Reasons for Growth: (1) **Human Activities**: Higher surface fouling discharges are a result of increased shipping, industrial activity, and maritime traffic. Inadequate Waste Management: Surface fouling builds up as a result of improper disposal techniques and insufficient waste treatment. (2) **Inadequate Cleaning Procedures:** Over time, contaminants can build up in heat exchangers due to infrequent or ineffective cleaning. The effective working of heat exchangers can be jeopardized by pollutants including oil, debris, and chemicals, which can result in decreased efficiency and higher operational expenses. The decreased efficiency of these essential components is a connection between increased operating costs and heat exchanger surface fouling.

The accumulation of pollutants on the surfaces of heat exchangers creates insulating layers that impede the movement of heat and lower cooling system performance.

Fuel consumption rises when efficiency declines because more energy is needed to produce the same amount of heat exchange. Increased fuel consumption results in higher operational costs, which affect the overall economic feasibility of ship operations. These costs include gasoline [3].

Thermal conductivity degradation is one of the main effects of pollutants on ship heat exchange systems. Pollutants reduce the efficiency of heat transmission among the fluid being used and the environment by building up a layer that serves as a thermal barrier. This reduced thermal conductivity raises the possibility of overheating and reduces heat exchange efficiency, both of which can seriously harm engine components.

The marine sector has been aggressively researching cutting-edge methods for maintaining and cleaning ship heat exchangers as a solution to these difficulties. To lessen the negative impacts of heat-exchangers surface heat-exchangers surface fouling and maintain the long-term effectiveness of heat exchange systems, efficient cleaning techniques must be developed [4].

There is now a number of cleaning methods being considered, from sophisticated chemical solutions to conventional mechanical approaches. In mechanical techniques, accumulated impurities are removed from heat exchanger surfaces using brushes, scrapers, or high-pressure water jets. These techniques can be useful, but they can also have drawbacks, such the requirement for a lot of downtime and the possibility of damaging sensitive components.

Conversely, chemical cleaning techniques use specifically designed chemicals to dissolve and extract contaminants without requiring mechanical assistance. These techniques provide a less intrusive and more effective way to maintain heat exchangers. To prevent any negative effects both the environment or any of the heat exchanger's components, nevertheless, considerable consideration must be given to the selection of the right cleaning chemicals [3].

Formulation of Problem. The smooth movement of products across seas is contingent upon the efficiency and dependability of ship power plant, which in turn affects the functioning of ship heat exchangers. The issue at stake involves the harmful effects of heat-exchangers surface heat-exchangers surface fouling on ship heat exchangers' capacity to operate at their best, which raises questions regarding the durability and sustainability of these vital components.

The main issue is that impurities build up on heat exchanger surfaces, interfering with the vital function of heat transmission. The collection of this material creates insulating layers that impede the effective transfer of heat between the surrounding environment and the working fluid. Thus, the reduced thermal conductivity directly jeopardizes the integrity of marine engines by reducing heat exchange efficiency and increasing the possibility of overheating [9].

Moreover, there are difficulties with the techniques used to maintain and clean ship heat exchangers. Even while traditional mechanical techniques are good at eliminating pollutants, they have disadvantaged such long downtime and the possibility of damaging sensitive components. Chemical cleaning techniques provide a less intrusive and more effective alternative, but their effects on the environment and material compatibility must be carefully considered [6].

The core of the issue is figuring out a long-term, practical way to lessen the damage that heat-exchangers surface heat-exchangers surface fouling causes to ship heat exchangers. Ensuring the continuous dependability and functionality of these vital components in the marine sector requires striking a balance between the requirement for effective cleaning techniques and environmental responsibility.

Analysis of recent research and publications: The numerous difficulties that the marine sector faces have been made clear by recent studies and publications on ship heat exchangers and their susceptibility to heat-exchangers surface heat-exchangers surface fouling. The impact of heat-exchangers surface heat-exchangers surface fouling on these essential components' functionality is becoming increasingly apparent as heat-exchangers surface heat-exchangers surface fouling levels rise worldwide, and researchers and professionals are working hard to find creative ways to deal with this pressing problem [7].

The kinds and sources of contaminants impacting ship heat exchangers have been the subject of several research. These consist of chemical pollutants, oil residues, and waste products from different human activities. For the purpose of creating efficient cleaning techniques suited to particular environmental circumstances and vessel operations, it is essential to comprehend the makeup and properties of these contaminants. The necessity for a thorough strategy to heat-exchangers surface heat-exchangers surface fouling control that considers the variety of pollutants encountered during marine activities is emphasized in recent publications [2; 5].

Recent studies have highlighted the link between pollutant buildup and thermal conductivity degradation in terms of the negative impacts of pollutants on heat exchanger performance. Experiments and computational models have been used to measure the effects of various pollutants' kinds and concentrations on the effectiveness of heat transfer. These evaluations contribute to the creation of focused solutions by offering insightful information about the ways by which heat-exchangers surface fouling impedes heat exchange activities [1; 5].

A prominent pattern observed in recent literature is the investigation of cutting-edge cleaning systems for ship heat exchange systems. Scholars are examining the efficacy of robotics cleaning equipment that can maneuver intricate heat exchanger arrangements to eliminate contaminants without requiring human assistance. These developments overcome some of the drawbacks of conventional mechanical approaches by reducing downtime while also improving cleaning precision and thoroughness [10]. Recent research has also focused on chemical cleaning agents, with the goal of creating solutions that are both ecologically benign and compatible with various materials. Publications stress how crucial it is to use cleaning products that reduce the environmental impact of maritime activities while simultaneously efficiently dissolving contaminants. Exploring bio-based cleaning agents along with additional environmentally friendly formulations has resulted from the search for sustainable alternatives and is in line with a growing focus on environmentally friendly procedures in the marine sector [11]. Additionally, the financial effects of pollutants on ship heat exchangers have been discussed in recent papers. Ship operators are becoming increasingly concerned about the financial impact of higher repair, maintenance, and replacement expenses as a result of damage caused by pollutants. Scholars are conducting cost-benefit analyses of various cleaning techniques, taking into account variables including fuel economy, operational downtime, and long-term maintenance needs [6].

To sum up, current studies and publications emphasize how urgent it is to address how heat-exchangers surface fouling affects ship heat exchangers. The wide range of subjects covered, from heat-exchangers surface fouling analysis to the development of cutting-edge cleaning methods, clearly demonstrates the multidisciplinary nature of this challenge. The collection of research results from these studies adds to the expanding volume of information that may guide business choices and legislative actions, eventually guiding the marine sector toward more resilient and sustainable solutions to the ever-increasing heat-exchangers surface fouling problems.

Formulation of goal of the article. This article's main objective is to present a thorough explanation of the complex impact of surface fouling on heat exchangers system. It also explores workable methods to reduce the negative impacts and maintain the long-term efficiency of ship power plant. The essay seeks to clarify the problems caused by heat-exchangers surface fouling, assess the existing level of knowledge, and provide strategic objectives for the marine sector and research community by combining insights from recent studies and publications.

The article's primary goal is to highlight the seriousness of the issue by outlining the many pollutants that have an effect on ship heat exchangers. The objective is to highlight the vital significance of recognizing the many different types of pollutants, including oil residue to chemical pollutants and debris, through an analysis of current research. The article seeks to build the groundwork for focused interventions in heat-exchangers surface fouling control by providing a comprehensive knowledge of various kinds and sources of pollutants.

The article aims to clarify the ways in which pollutants impair thermal conductivity and, in turn, the overall effectiveness of heat exchange processes by utilizing the results of recent research. This study emphasizes the need for creative and long-lasting solutions while laying the groundwork for a more in-depth investigation of cleaning techniques.

The goal's formulation includes an investigation of current developments in chemical agents and cleaning technology. In order to assess these methods' viability and efficacy in practical marine applications, the paper will look at robotic cleaning systems, sustainable formulations, and other innovative techniques. The objective also includes addressing economic factors, providing information on the financial effects of pollutants on ship heat exchange equipment and suggesting financially sensible solutions for ship operators.

Presentation of the main research material. Pollutant kinds and sources impacting ship heat exchangers vary and can have a major effect on these vital marine sector components' performance and efficiency. For the purpose of creating focused mitigation measures, it is vital to comprehend these contaminants. Below is an overview of the main categories and sources:

Types of Pollutants:

Oil Residues:

– Usually the result of spills, leaks, or incorrect disposal techniques;

– May accumulate as a thin layer on heat exchanger the surfaces, preventing heat transfer.

Chemical Contaminants:

– Result from runoff, cargo residues, and industrial wastes; Contain corrosive elements that hasten the deterioration of heat exchanger components.

– Could accumulate and reduce heat conductivity.

Debris:

– May cause friction and abrasion of heat exchanger surfaces.

– Contains solid particles including materials for plastics, debris, and organic debris.

– Gets into heat exchangers through the saltwater intake, possibly causing fouling and lowering efficiency.

Sources of Pollutants:

Ship exhaust:

– Particles and chemical compounds are released into the air and water by engine exhaust.

– Pollutant collection on heat exchanger surface can be facilitated by atmospheric deposition.

Industrial Operations:

– Chemical emissions from manufacturing operations can enter heat exchangers;

– emissions from industrial facilities add a variety of contaminants to open and coastal waterways.

Runoff and Urban Releases:

– Pollutants from highways, farms, and urban areas are carried into water bodies by rainfall runoff.

– Urban discharges contaminate coastal habitats with untreated wastewater and storm water.

Accidental leaks:

– Heat exchangers are directly at risk from oil leaks resulting from offshore drilling or shipping mishaps.

– Chemical spills can pollute seawater and have an impact on heat exchanger performance. Examples of these spills include cargo leaks.

Natural Sources:

– Particulates and gases can be released into the atmosphere by natural occurrences such as volcanic eruptions and wildfires.

– These organic sources add to the total amount of heat-exchangers surface fouling in marine habitats.

Creating efficient cleaning and maintenance plans requires an understanding of the makeup and source of these contaminants. Ship heat exchanger lifetime and efficiency may be increased while reducing environmental effect by the maritime sector by addressing the unique features of pollutants, whether via mechanical or chemical techniques.

The relationship between the buildup of pollutants and the decrease in thermal conductivity; Understanding the relationship between the buildup of pollutants and the decrease in thermal conductivity in ship heat exchangers is crucial to comprehending how heat-exchangers surface fouling affects these vital parts. Pollutant buildup on heat exchanger surface can reduce thermal conductivity by impeding the effective transmission of heat among the working fluid and the environment. Understanding this relationship is essential to creating focused remedies that preserve heat exchanger performance at its best. Here are some salient points about this relationship [9]:

1. Formation of Insulating Layers: pollutants, including chemicals, dirt, and oil residues, accumulate on the surfaces of heat exchangers. By acting as insulating barriers, these layers prevent heat from being transferred from the fluid moving in the exchanger to the surrounding area.

2. Risk of Overheating: The heat exchanger system is more susceptible to overheating when thermal conductivity drops. Overheating can have detrimental effects that jeopardize the vessel's safety and dependability, such as increased wear and even damage to engine components.

3. The correlation highlights the importance of routine cleaning and maintenance of shipboard heat exchangers to prevent and mitigate the negative effects of pollutant buildup. The goals of maintenance procedures are to eliminate pollutants, restore thermal efficiency, and extend the lifespan of the heat exchanger elements.

4. Quantitative Analysis: To study the association numerically, recent research has used both computer models and experimental experiments. Experimental studies involve testing in the real world, measuring thermal conductivity in controlled circumstances to validate theoretical predictions. Computer models simulate the impact of various kinds and amounts of pollutants on thermal conductivity, offering insights into the processes required.

Assessing the viability and efficiency of new cleansing techniques for ship heat exchangers is essential to finding workable solutions that not only deal with heat-exchangers surface fouling problems but also take the environment and economy into account (Table 1). This is a summary of the main elements of the assessment procedure [9; 10; 11].

Table 1

Marine Heat Exchanger Cleansing Techniques: A Comprehensive Viability and Efficiency Assessment for Environmental and Economic Sustainability

		Pros	Cons
Effectiveness Assessment	Robotic Cleaning System	Compared to traditional human techniques, automation reduces downtime and improves cleaning effectiveness and efficiency by accessing complicated configurations and tough regions. It also enables accurate cleaning without requiring substantial removal of heat exchanger elements.	The cost of the initial investment might be substantial; servicing and programming requirements should be taken into account.
	Chemical Cleaning agent	• Suitable for a variety of heat exchanger types; • Highly efficient in dissolving and eliminating different impurities without the need for mechanical intervention; • Formulated to be material-compatible and ecologically safety	• Choosing the right cleaning products is essential; certain formulations may have an impact on the environment. • Waste management and chemical disposal need to be carefully considered.
		Robotic Cleaning Systems:	Chemical Cleaning Agents
Sustainability Considerations	Environmental Impact	• In general, robotic systems are less harmful to the environment than certain chemical cleaning products. • Reducing the use of hazardous chemicals helps maintain a sustainable ecosystem.	• The transition to more environmentally friendly formulations reduce harmful impacts on marine environments. • Formulations that are non-toxic and biodegradable conform to sustainable principles.

	Resource Efficiency	By focusing on particular areas and eliminating needless cleaning, it is possible to maximize resource efficiency. Additionally, automated methods lessen the need for physical work, which helps conserve resources.	• Appropriate formulation and application guarantee effective elimination of pollutants, reducing the amount of chemicals needed. • It is crucial to take resource usage into account while producing chemical agents.
Economic Viability		• Long-term benefits from less downtime and improved cleaning efficiency may balance the expenses of the initial investment. • The scope of ship operations and the amount of required cleaning have an impact on cost-effectiveness.	• It's important to take into account the costs of buying and discarding cleaning supplies. • Longer equipment lifespans and better heat exchanger performance can result in economic benefits.
Long-Term Maintenance Implications		Utilizing robotic devices on a regular basis can help with long-term maintenance planning and keep pollutants from building up. • It is important to keep an eye on and evaluate system performance on a regular basis.	• Regular use of the right cleaning products helps reduce the long-term harm caused by a buildup of pollutants. • For extended efficacy, cleaning solutions' compatibility with heat exchanger components must be taken into account.

Source: author's own development

Improving the cleaning techniques for ship heat exchangers is essential to preserving maximum efficiency and reducing the environmental effect. Here are a few ideas for cleaning methods:

Automation and Robotics:

– Install robotic cleaning devices with sophisticated sensors and software.

– Give robots the freedom to move through complex heat exchanger systems for accurate and effective cleaning.

– Cut down on the amount of physical labor required and downtime.

Water Jets at High Pressure:

For mechanical cleaning, use water jets with high pressure.

– Eliminate contaminants efficiently while protecting the surfaces of the heat exchanger.

– Boost productivity and cut back on the usage of toxic cleaning supplies.

– Cleaning using ultrasonic:

Use ultrasonic cleaning techniques to get rid of impurities.

– Create tiny bubbles with high-frequency sound waves to disturb and loosen toxins.

– ideal for confined spaces and complex heat exchanger systems.

Cleaning brushes without abrasives:

– Create cleaning brushes that aren't harsh using cutting-edge materials.

– Scrub efficiently while avoiding damaging the heat exchanger plates or tubes.

– Incorporate with robotic systems to achieve accurate control.

Chemical Agents That Are Kind to the Environment:

– Investigate and create green cleaning products.

– Create substances that efficiently dissolve contaminants while having no negative effects on the environment.

– Think of non-toxic and biodegradable compositions.

Creative Designs for Heat Exchangers:

– Examine heat exchanger designs that are naturally impervious to the accumulation of pollutants.

– Improve the surface materials to prevent fouling and stickiness.

– Encourage the heat exchanger's internal self-cleaning systems.

Systems for Real-Time Monitoring:

– Install equipment for monitoring heat exchanger performance in real time.

– To measure surface fouling levels and efficiency, use sensors.

– Allow for proactive cleaning that isn't based on rigid timetables but rather on real circumstances.

Chemical cleaning chemicals that are employed on ship heat exchangers have the potential to pollute water, cause ecotoxicity, accumulate in the environment, modify the chemistry of the water, and be permanent. To mitigate this, the industry is moving toward ecologically friendly formulations, with a strong emphasis on closed-loop systems for responsible usage and regulatory compliance as well as biodegradability, non-toxicity, and green chemistry.

The effects of pollutants on ship heat exchangers and their practical significance

Pollutant influence on ship heat exchangers has a variety of practical implications, from maintenance costs and operational efficiency to environmental effects. It is imperative that the marine sector comprehends and tackles these ramifications to guarantee the dependable and enduring operation of ships. Here, we examine the application and consequences of the way contaminants impact ship heat exchangers [8; 12]:

1. Diminished Efficiency of Operations:

– Main Problem: Pollutants including chemicals, trash, and oil residues build insulating layers on heat exchanger surfaces, which prevents heat from being transferred efficiently.

– Practical Implication: to accomplish the needed heat exchange, more energy must be used since reduced thermal conductivity lowers operating efficiency. Ship operators suffer from increased fuel consumption and operating expenses as a result.

2. Elevated Risk of Overheating:

– Main Problem: The weakened heat transfer efficiency makes ship engines more susceptible to overheating.

– Practical Implication: Engine component integrity is directly jeopardized by overheating, which increases the risk of premature wear, malfunctions, and unscheduled downtime. Reducing this risk is essential to preserving the dependability and safety of ships.

3. Increased Maintenance Expenses:

– Main Problem: Damage caused by pollutants requires more regular and thorough repair.

– Practical Implication: Increased corrosion and damage on the heat exchanger components results in greater maintenance expenses for ship operators. These costs contribute to the total operating expenditure and include cleaning, repairs, and possible replacements.

4. Prolonged Rest Period for Cleaning:

– Main Problem: Manual involvement during traditional cleaning procedures may necessitate a large amount of downtime.

– Practical Implication: Schedules for vessels and operational effectiveness are adversely affected by prolonged downtime. the amount of time the ship is grounded for cleaning, the more of an economic hit it takes on trade routes and maritime businesses.

5. Environmental Impact:

• Main problem: Improper management of pollutants may have negative consequences for the marine ecosystem.

– Practical Implication: Heat-exchangers surface fouling of the environment might result from unintentional spills or poor cleaning techniques. Adherence to environmental standards is vital in order to avert legal results and preserve a favorable industry reputation.

6. Safety and Operational Reliability Issues:

– Key Issue: The dependability and security of ship operations are jeopardized by unchecked heat-exchangers surface fouling buildup.

– Practical Implication: Keeping timetables and fulfilling transportation obligations depend heavily on the dependability of boats. When crucial components are impacted by heat-exchangers surface fouling, safety concerns arise since this might result in maritime mishaps or disasters.

7. Effect on Equipment Lifespan Over Time:

– Main Problem: Heat exchanger components may have a shortened lifespan as a result of ongoing heat-exchangers surface fouling exposure.

– Practical Implication: Early corrosion and wear may necessitate more frequent replacements, raising the upfront costs for vessel owners. Heat exchanger lifespan must be taken into account for fleet management to be both economical and sustainable.

8. Regulatory Compliance:

– Main Concern: The marine industry's cleaning and heat-exchangers surface fouling discharge procedures are subject to strict environmental rules.

– Practical Implication: In order to comply with these laws, ship operators must implement eco-friendly cleaning techniques and technology. There may be penalties, fines, and negative publicity for noncompliance.

An advanced device called the Automated Robotic Cleaning Module is intended to clean ship heat exchangers effectively and independently. It consists of many fundamental components:

Cameras and Sensors:

– advanced sensors for real-time environmental sensing, such as cameras and proximity sensors.

– gives the robot the ability to go through intricate heat exchanger layouts and locate spots that need maintenance.

Modular attachments:

– Adaptable cleaning attachments to accommodate a range of heat exchanger configurations.

– modules designed to specialize in different kinds of pollutants, guaranteeing thorough cleaning.

Navigation that can be programmed:

– Accurate programming skills for self-navigating systems.

– pathways for cleaning that may be altered, enabling the robot to adjust to different heat exchanger shapes.

Superior Efficiency Motors:

– Strong and effective motors for accurate attachment operation and movement.

– guarantees the best possible cleaning power and flexibility to various surface materials.

Wireless Interaction:

– Wireless connectivity that is integrated for data transfer and remote control.

– allows for real-time monitoring and modification, increasing operational effectiveness.

System for Avoiding Collisions:

– makes use of sophisticated algorithms to prevent collisions.

– guarantees the robot's safe navigation in confined areas and complex heat exchanger designs.

Energy-Saving Architecture:

– integrates systems and parts that use less energy for extended operation.

– Effective power control to increase cleaning duration and coverage.

Interface User:

– Simple user interface for monitoring and operating remotely.

– gives operators the ability to monitor cleaning progress, make changes in real time, and get updates on the state of the system.

Pollutant development on heat exchanger walls is impacted by a number of variables, including vessel activity, operational circumstances, and water quality. Growth rates vary, but in marine environments, constant contact to contaminants and saltwater can cause them to occur rather quickly. When a visible coating of impurities reduces heat exchanger performance, routine cleaning is recommended. The frequency is determined by variables such as water quality, vessel utilization, and the efficiency of surface fouling control methods.

It is essential to develop real-time monitoring systems in order to regulate pollutants during operation. Regularly assess surface fouling levels and efficiency with sensors. Take preventative action by using robotic cleaning that is automated to stop excessive accumulation. Remainders may be collected by setting up closed-loop filtering systems, and using green chemical techniques reduces environmental effect. To guarantee effective heat exchanger performance, optimal management necessitates striking a balance between environmental responsibility, operational needs, and proactive maintenance.

Given the variety of ship power plants and the range of pollutants connected with each kind, choosing certain heat exchanger types is undoubtedly an intelligent decision. For example:

Heat exchangers with shell and tubes:

– They are frequently used in maritime applications, however they can become fouled by biological growth and detritus.

– Think of automated robotic cleaning systems equipped with brushes for effectively targeting the exterior and inner surfaces of tubes.

Heat exchangers on plates:

– prone to scale from saltwater salts and clogging from particles

– Use high-pressure water jet systems to clean mechanically, paying special attention to keeping plates apart for best results.

Heat exchangers that run on air:

– susceptible to dust buildup and flying debris, which reduces cooling effectiveness.

– For accurate cleaning that doesn't harm finned surfaces, use automated robotic cleaning with air-assisted nozzles.

Heat exchangers with fins:

– prone to corrosion and fouling, particularly in settings high in salt.

– Use high-pressure water jet systems in conjunction with chemical cleaning solutions designed to prevent corrosion.

Selecting certain heat exchanger types enables a focused and customized approach to cleaning techniques, guaranteeing the most effective and effective elimination of contaminants while reducing the risk of equipment damage.

Conclusion

In conclusion, the marine sector has to give the effect of heat-exchangers surface fouling on the functioning of ship heat exchangers immediate attention that not much found on the literature. The development of efficient cleaning techniques becomes critical as long as contaminants continue to jeopardize the effectiveness of these vital components. In the heat-exchangers surface fouling issues, maintaining the lifetime and optimum operation of ship heat exchangers requires striking an equilibrium among the environment and operational efficiency.

In short, the connection between the buildup of pollutants and the loss of thermal conductivity highlights the need of taking proactive actions to tackle heat-exchangers surface fouling-related issues in ship heat exchangers. A thorough comprehension of this relationship guides the creation of efficient cleaning techniques and maintenance plans, guaranteeing the continued dependability and efficiency of ship engines in the context of growing heat-exchangers surface fouling issues.

Recent cleansing methods for ship heat exchangers are evaluated by doing a thorough examination of their long-term maintenance implications, economic viability, sustainability, and efficacy. In the overall scheme of heat-exchangers surface fouling control, making well-informed decisions that support the objectives of the marine sector requires an integrated strategy that considers both the effects on the environment and operational effectiveness.

Beyond technical concerns, the practical complications of pollutant effect on ship heat exchangers include financial, ecological, and safety factors. In order to minimize these effects and guarantee the ongoing effectiveness and dependability of marine operations, it is imperative that proactive maintenance procedures, cutting-edge cleaning technologies, and regulatory compliance be followed.

Using sensor technology, flexibility, and intuitive user interfaces, the Automated Robotic Cleaning Module is a state-of-the-art system that maximizes ship heat exchanger cleaning effectiveness and efficiency while reducing human involvement and downtime.

BIBLIOGRAPHY

1. A Review of Biofouling of Ships' Internal Seawater Systems / I. Davidson et al. *Frontiers in Marine Science*. 2021. Vol. 8. URL: https://doi.org/10.3389/fmars.2021.761531 (date of access: 09.12.2023).
2. A conceptual framework for waste heat recovery from compression ignition engines: Technologies, working fluids & heat exchangers / O. Douadi et al. *Energy Conversion and Management: X*. 2022. Vol. 16. P. 100309. URL: https://doi.org/10.1016/j.ecmx.2022.100309 (date of access: 09.12.2023).
3. A recent review on waste heat recovery methodologies and applications: Comprehensive review, critical analysis and potential recommendations / O. Farhat et al. *Cleaner Engineering and Technology*. 2022. Vol. 6. P. 100387. URL: https://doi.org/10.1016/j.clet.2021.100387 (date of access: 09.12.2023).
4. ICES Viewpoint background document: Impact from exhaust gas cleaning systems (scrubbers) on the marine environment (Ad hoc) / I.M. Hassellöv et al. *ICES Scientific Reports*. 2020. 2:86. 40 p. http://doi.org/10.17895/ices.pub.7487.
5. Thermal design and analysis of an organic rankine cycle system utilizing the main engine and cargo oil pump turbine based waste heats in a large tanker ship / O. Konur et al. *Journal of Cleaner Production*. 2022. P. 133230. URL: https://doi.org/10.1016/j.jclepro.2022.133230 (date of access: 09.12.2023).
6. Analysis of Removing Barnacles Attached on Rough Substrate with Cleaning Robot / C. Li et al. *Journal of Marine Science and Engineering*. 2020. Vol. 8, no. 8. P. 569. URL: https://doi.org/10.3390/jmse8080569 (date of access: 09.12.2023).
7. Lion S., Vlaskos I., Taccani R. A review of emissions reduction technologies for low and medium speed marine Diesel engines

and their potential for waste heat recovery. *Energy Conversion and Management*. 2020. Vol. 207. P. 112553. URL: https://doi.org/10.1016/j.enconman.2020.112553 (date of access: 09.12.2023).

8. An advanced marine engine waste heat utilization scheme: Electricity-cooling cogeneration system integrated with heat storage device / T. Ouyang et al. *Energy Conversion and Management*. 2021. Vol. 235. P. 113955. URL: https://doi.org/10.1016/j.enconman.2021.113955 (date of access: 09.12.2023).
9. Peter O., Mohamed A., Emmanuel V., & Tochukwu N. Corrosion effects on low carbon steel marine heat exchanger. *International Journal of Advanced Science and Technology*. 2020. Vol. *29*(7). P. 10066-10072.
10. Hornbill: A Self-Evaluating Hydro-Blasting Reconfigurable Robot for Ship Hull Maintenance / V. Prabakaran et al. *IEEE Access*. 2020. Vol. 8. P. 193790–193800. URL: https://doi.org/10.1109/access.2020.3033290 (date of access: 09.12.2023).
11. Design and analysis of a wheel-leg compound variable curvature ship hull cleaning robot / B. Wang et al. *Ocean Engineering*. 2022. Vol. 266. P. 112755. URL: https://doi.org/10.1016/j.oceaneng.2022.112755 (date of access: 09.12.2023).
12. Yang Z., Korobko V., Radchenko M., & Radchenko R. Improving Thermoacoustic Low-Temperature Heat Recovery Systems. *Sustainability*. 2022. Vol. 14(19). P. 12306.

REFERENCES

1. Davidson, I., Cahill, P., Hinz, A., Kluza, D., Scianni, C., & Georgiades, E. (2021). A review of biofouling of ships' internal seawater systems. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.761531.
2. Douadi, O., Ravi, R., Faqir, M., & Essadiqi, E. (2022). A conceptual framework for waste heat recovery from compression ignition engines: Technologies, working fluids & heat exchangers. *Energy Conversion and Management: X*, *16*(100309), 100309. https://doi.org/10.1016/j.ecmx.2022.100309
3. Farhat, O., Faraj, J., Hachem, F., Castelain, C., & Khaled, M. (2022). A recent review on waste heat recovery methodologies and applications: Comprehensive review, critical analysis and potential recommendations. *Cleaner Engineering and Technology*, *6*(100387), 100387. https://doi.org/10.1016/j.clet.2021.100387.
4. Hassellöv, I.M., Koski, M., Broeg, K., Marin-Enriquez, O., Tronczynski, J., Dulière, V., Murray, C., Bailey, S., Redfern, J., de Jong, K., Ponzevera, E., Belzunce-Segarra, M.J., Mason, C., Iacarella, J.C., Lyons, B., Fernandes, J.A. and Parmentier, K. (2020). ICES Viewpoint background document: Impact from exhaust gas cleaning systems (scrubbers) on the marine environment (Ad hoc). *ICES Scientific Reports*. 2:86. 40 p. http://doi.org/10.17895/ices.pub.7487.
5. Konur, O., Yuksel, O., Korkmaz, S. A., Colpan, C. O., Saatcioglu, O. Y., & Muslu, I. (2022). Thermal design and analysis of an organic rankine cycle

system utilizing the main engine and cargo oil pump turbine based waste heats in a large tanker ship. *Journal of Cleaner Production*, *368*(133230), 133230. https://doi.org/10.1016/j.jclepro.2022.133230.

6. Li, C., Wang, G., Chen, K., Jia, P., Wang, L., Wang, X., & Yun, F. (2020). Analysis of removing barnacles attached on rough substrate with cleaning robot. *Journal of Marine Science and Engineering*, *8*(8), 569. https://doi.org/10.3390/jmse8080569.
7. Lion, S., Vlaskos, I., & Taccani, R. (2020). A review of emissions reduction technologies for low and medium speed marine Diesel engines and their potential for waste heat recovery. *Energy Conversion and Management*, *207*(112553), 112553. https://doi.org/10.1016/j.enconman.2020.112553.
8. Ouyang, T., Wang, Z., Zhao, Z., Lu, J., & Zhang, M. (2021). An advanced marine engine waste heat utilization scheme: Electricity-cooling cogeneration system integrated with heat storage device. *Energy Conversion and Management*, *235*(113955), 113955. https://doi.org/10.1016/j.enconman.2021.113955.
9. Peter, O., Mohamed, A., Emmanuel, V., & Tochukwu, N. (2020). Corrosion effects on low carbon steel marine heat exchanger. *International Journal of Advanced Science and Technology*, *29*(7), 10066–10072.
10. Prabakaran, V., Vu Le, A., Kyaw, P. T., Mohan, R. E., Kandasamy, P., Nguyen, T. N., & Kannan, M. (2020). Hornbill: A self-evaluating hydro-blasting reconfigurable robot for ship hull maintenance. *IEEE Access: Practical Innovations, Open Solutions*, *8*, 193790–193800. https://doi.org/10.1109/access.2020.3033290.
11. Wang, B., Ni, Z., Shen, Y., Zhang, S., Shen, Q., & Niu, X. W. (2022). Design and analysis of a wheel-leg compound variable curvature ship hull cleaning robot. *Ocean Engineering*, *266*(112755), 112755. https://doi.org/10.1016/j.oceaneng.2022.112755.
12. Yang, Z., Korobko, V., Radchenko, M., & Radchenko, R. (2022). Improving Thermoacoustic Low-Temperature Heat Recovery Systems. *Sustainability*, *14*(19), 12306.