https://doi.org/10.22306/al.v11i2.516 *Received: 27 Dec. 2023; Revised: 23 Jan. 2024; Accepted: 20 Mar. 2024*

Reliability analysis of marine diesel engines vs. industrial diesel engines: a comparative approach

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Keywords: reliability analysis, operational conditions, maintenance practices, heat exchanger.
Abstract: The study presents a comparative analysis of the reliability of marine and industrial diesel engines, emphasizing the role of heat exchangers. Diesel engines in marine vessels and industrial applications face distinct challenges, influencing their reliability. This paper examines these differences, focusing on operational conditions, load profiles, redundancy, safety measures, and maintenance practices. Three types of heat exchangers (Fin fan, Plate, and Shell & Tube) are analyzed which are used in these engines. The assessment covers failure rates, Mean Time to Failure (*MTTF*), and the impact of independent and dependent failures on reliability. The study identifies unique failure modes like insufficient heat transfer, external leakage, parameter deviation, and structural deficiencies and their differing impacts in marine and industrial contexts. The research highlights the sensitivity of marine engine heat exchangers to seawater-induced corrosion and fouling, affecting heat transfer efficiency. In contrast, industrial engines display varying failure characteristics due to system controls and operational parameters. A significant finding is the decrease in reliability over time for all heat exchanger types, underscoring the importance of maintenance and monitoring. Our results show slight shifts in failure rates due to equipment inefficiencies markedly affecting heat exchangers' operational lifecycles. The study concludes with a necessity for tailored maintenance strategies and design considerations for marine and industrial diesel engine heat exchangers. This focused approach offers insights into optimizing diesel engine reliability, particularly by understanding the main role of heat exchangers.

1 Introduction

The reliability of diesel engines plays a vital role in marine (ships' main engine) and industrial sectors (standby power generators for hospitals or data centers, construction equipment, etc.), where these powerhouses serve critical roles in various applications. By exploring key factors influencing reliability, such as environmental conditions, load profiles, redundancy, safety measures, and maintenance practices, this paper aims to illustrate the different distinct challenges and considerations between marine diesel engines and industrial diesel engines.

There is a lot of diversity in the literature addressing the reliability of different engine components within different environmental conditions and operation specifications. In their study, Jing et al. indicated that the material properties of engine components are not the main cause of failures. The study focused on the reliability of diesel engine cylinder heads through fatigue failure analysis and the influence of working loads; gas force amplitude was the main factor, and thermal loads were the secondary factors affecting the component's reliability. The applied method through the study was the finite element simulation [1]. Dolas et al. presented a reliability analysis of the cooling system of diesel engines used for compressor application, depending on Mean Time to Failure (*MTTF*) data, Weibull distribution analytical least square method, and Minitab 16.1R Software. The obtained failure rate value was lower than the empirical values, and the values calculated were based on the Weibull distribution [2]. Anantharaman et al. present an integration of the Markov model (for constant failure components) and the Weibull failure model (for wearing out components) to provide a realistic and practical analysis of the marine diesel engine with a case study of turbocharger effects on the overall engine reliability and safety [3].

Dionysiou et al. investigated the safety improvements of the lubricating oil system of marine diesel engines by applying safety, reliability, availability, and diagnosability analyses. Reliability Block Diagrams were used to estimate the reliability and availability metrics at different design modifications. The analysis also included a combination of Failure Modes, Effects and Criticality Analysis, and the Functional Fault Tree Analysis methods. The results show that the most critical components in the lubricating oil system are the suction strainer (Reliability Importance 57.2%) and the lubricating oil pump (Reliability Importance 32.27%). Seven additional sensors were introduced to enhance the system design, and the investigated alternative designs exhibit significantly lower probabilities of failure and higher availability values [4]. Kirolivanos et al. investigated the reliability of marine dual-fuel engines compared to conventional diesel engines. The research results were 8.48% for diesel engine reliability mean value and 8.84% for dual-fuel engines, which means dual-fuel engines are more reliable than diesel engines. The results also offer insights into the relationship between the system's reliability and the planned maintenance strategies [5]. Other studies focused on improving the reliability of marine diesel engine subsystems by analyzing the reliability metrics at different conditions and designs. These studies analyze key performance indicators such as the Mean Time to Repair, Failure Rate, and Mean Time Between Failures [6,7]. Issa et al. focused on analyzing the impacts of low engine load (below 30%) and environmental conditions such as temperature, humidity, abrasive dust, and corrosive environments on the operation of modern diesel generators. Their findings reveal that prolonged operation of diesel engines at low loads can result in deterioration, which means that running these engines for extended periods at low loads might cause irreversible damage. Additionally, there's a noticeable decrease in engine performance when these engines exceed specific environmental limits [8]. Eriksen et al. examine the limitation on reliability improvement through redundancy on ship components and how the length of the ship course will affect it. The study also addressed the effects of independent and dependent failures on reliability [9]. Some research studied the possibilities of increasing ship operational reliability by implementing a new maintenance strategy. The study calculations identified the system's critical components while advising more practical maintenance activities [10,11].

By incorporating these studies, we can build upon their methodologies and findings to comprehensively compare marine and industrial diesel engine reliability changes. Drawing from their insights, we aim to enrich the understanding of how environmental conditions, load profiles, redundancy, safety measures, and maintenance practices collectively contribute to the reliability and performance of these engines.

The paper is organized as follows: first, a demonstration of distinct environmental conditions and load profiles in both marine and industrial diesel engines are presented in Section 2. After that, the critical role of redundancy and safety measures in ensuring reliability is evaluated in Section 3. Then, the maintenance practices and strategies and their influences on reliability are explained in Section 4. The methods and equations used in the reliability and maintainability engineering field are shown in Section 5. The final part addresses the paper's reliability results and discusses the possible solutions to enhance reliability in Section 6.

The paper's main added value is the holistic examination of reliability factors combined with practical insights and real case studies. The study offers a novel comparative analysis of heat exchanger reliability in marine and industrial diesel engines, highlighting specific failure modes, the impact of environmental conditions, and the importance of tailored maintenance and design strategies for enhanced efficiency and longevity.

2 Environmental conditions and load profiles for marine and industrial diesel engines

The wide range of environmental conditions and load demands significantly affects the performance of both marine and industrial diesel engines. However, marine diesel engines face more significant challenges due to the dynamic load demands and harsh environmental conditions. Marine diesel engines must withstand frequent load fluctuations and saltwater exposure while incorporating features to manage vibrations, rolling, and pitching. On the other hand, stationary or industrial diesel engines benefit from more controllable environments and generally more predictable load profiles, leading to a potentially longer lifecycle and optimized operational efficiency.

2.1 Environmental conditions

Diesel engine performance requires operation within certain limits for environmental conditions such as temperature, humidity, abrasive dust, and corrosive environments. When an engine exceeds these limitations, a noticeable decrease in performance will appear [8]. On the other hand, marine diesel engines are designed to operate efficiently and effectively while considering various environmental factors. Marine diesel engines are designed with a combination of advanced technologies, emission control systems, and operational considerations to navigate through changing environmental conditions while following international and regional emission regulations such as the International Maritime Organization's (IMO) and MARPOL ANNEX VI regulations [12]. Table 1 demonstrates the different environmental conditions encountered by diesel engines during the operation.

The comparative analysis of marine and industrial diesel engines investigates their unique challenges and operational conditions, providing the background for future research and technological improvements. It offers practical insights for industry experts to improve efficiency, safety, and environmental compliance, serving academic and practical needs in engine management.

Table 1 Comparison of environmental conditions for marine and industrial engines

Marine Diesel Engines	Industrial Diesel Engines
• Operate in highly corrosive and humid marine environments with exposure to saltwater.	• Operate in a controlled indoor environment, typically less exposed to corrosive elements.
• High humidity and saltwater can accelerate corrosion and impact electrical systems.	• Temperature and humidity control can be easier to manage, reducing the impact on components and electrical systems.
• Vibration and rolling from wave-induced motion can affect engine components.	• Vibration and rolling factors are generally lower but might still be relevant depending on the application.
• Introduce more safety challenges due to marine environments' corrosive and dynamic nature.	• Offer a safer working atmosphere for operators, with reduced risks associated with these factors.
• Designed for continuous operation during long sea trips.	• Have more varied applications and usage patterns.
• Components are designed to be robust, but maintenance is still necessary to prevent unexpected failures and ensure reliability. • Maintaining different components can be difficult due to the limited and tight spaces on vessels	• The frequency and approach to maintenance vary based on the specific applications and requirements. • Have more accessible components.

2.2 Load profiles and operation demands for marine and industrial diesel engines

The load profile of an engine describes the relationship between the power output and the engine's speed. It depends on the application, design, and operation of the engine. Table 2 demonstrates the load spectrum based on the percentage of continuous maximum rating for a better understanding of engine load differences and demands.

Table 2 Diesel engine load scenarios and operation demands

Applied Load	Description	Marine Diesel Engine	Industrial Diesel Engines
0-25%	Extreme low load	Standby mode: The ship is docked in a port and needs to maintain basic operations (lighting and onboard systems)	Only during minimal power demand
25-40%	Low load	Slow cruising Calm waters	Slight increase in power demand
40-80%	Regular operation load	Moderate sea conditions	Normal working hours
80-90%	High load	Rough seas Tight schedule	Substantial demand for power
90-100%	Extreme high load	Rapid acceleration Rough seas	Peak power demand

Marine diesel engines are used for propulsion and onboard power generation of ships and offshore platforms. Depending on the vessel's speed, sea conditions, and maneuverings, these engines must operate in various unpredictable load conditions, from low to extremely high. Marine diesel engines must also comply with strict emission regulations for marine environments [12]. Industrial diesel engines are used for power generation and mechanical drive of industrial equipment, such as pumps, compressors, etc. These engines must operate in steady or variable load conditions, depending on the demand and the system stability, and must meet different emission standards for different regions and applications. In the case of marine diesel engines, dynamic transient loads occur during the engine's operation, such as acceleration, deceleration, change of propeller pitch, etc. These changes add additional complexity and affect the friction, wear, lubrication, and vibration of the engine components, such as the piston, cylinders, and crankshaft. These effects can influence the performance and lifecycle of the engine components, as well as fuel consumption and emissions [8]. In contrast, industrial diesel engines typically encounter more progressive and predictable load changes. Industrial applications often involve steady or slowly varying loads. Unlike the rapid and frequent load shifts of marine engines, industrial engines have more stable operational profiles. This allows for better load management, reduced wear and tear on components, and optimized fuel consumption [8].

Understanding these load profiles and their implications is vital for designing, operating, and effectively maintaining marine and industrial diesel engines. It enables engineers to optimize engine performance, enhance reliability, and mitigate environmental impacts, all while ensuring compliance with relevant regulations.

In conclusion, the varying load demands of marine and industrial diesel engines reflect the complexity of their respective operational environments. The dynamic and unpredictable load shifts encountered by marine engines emphasize the need for flexible designs and effective maintenance. In contrast, industrial engines' steadier and more predictable load transitions enable strategic optimization and prolonged reliability. Considering these differences is fundamental for the practical engineering, operation, and maintenance of these critical engines, ensuring that they meet the demands of their applications with precision and durability.

3 The role of redundancy and safety measures in increasing diesel engines' reliability

Redundancy involves incorporating standby or backup components, systems, or processes within a system. This step provides an alternative pathway in case of failure in the primary component. In marine and industrial diesel engines, redundancy can contribute significantly to reliability. Downtime can lead to severe consequences in critical applications like marine vessels and power plants. Redundancy reduces the risk of complete system failure, protecting against potential hazards and economic losses. In addition, it enhances the system's ability to tolerate faults, especially in environments where component failures due to extreme conditions or wear are more likely, such as corrosive marine environments. Redundancy is vital in marine diesel engines due to the often-challenging operating environments. Ships must be able to navigate safely, even during engine failures. As a result, marine engines typically incorporate higher levels of parallel redundancy, such as multiple main engines, generators for various onboard systems, and propulsion systems, such as propellers or thrusters. This ensures that a single point of failure does not jeopardize the ship's safety or ability to reach port. In critical cases, maritime regulations often mandate redundancy to prevent accidents and environmental disasters. However, there are limitations to the reliability level that can be reached through redundancy in real applications [9,13]. While redundancy is also important in industrial applications, the degree of redundancy might vary depending on the criticality of the operation. Some industrial operations may prioritize redundancy, where downtime can lead to significant financial losses or safety hazards. However, not all industrial applications require the same level of redundancy as marine engines. Industrial setups may have backup power systems and safety measures to mitigate disruptions but may not always reach the extensive redundancy seen in marine vessels [14].

Safety measurements include various practices and technologies designed to prevent accidents and reduce risks, and it is also designed to protect crews, the environment, and machines [15,16]. In diesel engines, safety measurements contribute significantly to overall reliability. These safety measurements include the measurement of the emergency shutdown systems, alarms, and protective barriers. In addition, prioritizing the safety of operators working with or around diesel engines enhances the operation's overall reliability by minimizing the potential for accidents and injuries. Other safety measurements include measurements that address emissions, spills, and leaks and contribute to the reliability of these engines by ensuring compliance with environmental regulations [17,18]. Safety measurements also focus on preventive maintenance and regular inspections, which reduce the possibility of unexpected failures and disruptions. Marine diesel engines operate in complex and often unpredictable environments, including open seas, with potential hazards like storms and collisions. As a result, safety measurements include comprehensive navigation systems, life-saving equipment, and emergency response protocols. These measurements are designed to ensure the safety of passengers, crew, and the marine environment. Safety measurements for industrial diesel engines are specific to the industrial environment and associated risks. However, the scope and extent of safety measurements may not be as extensive as those required for marine engines, such as the immediate risks and environmental consequences, which may differ.

In summary, both marine and industrial diesel engines prioritize reliability, redundancy, and safety measurements, adjusting their emphasis based on the specific operating environment and associated risks. Marine engines, due to dealing with challenging and regulated maritime conditions, often incorporate higher levels of redundancy and more comprehensive safety measurements to ensure the safety of lives and the environment. Industrial engines adapt their redundancy and safety measurements based on the level of criticality of their operation and the potential consequences of failure.

4 The role of maintenance in increasing diesel engines' reliability

Maintenance practices refer to the specific tasks, activities, and routines that are carried out to ensure the proper functioning, reliability, and longevity of equipment, machinery, and systems. On the other hand, maintenance strategies are wider and more strategic approaches to managing maintenance activities. These strategies involve deciding when and how to perform maintenance based on equipment criticality, cost considerations, operational requirements, and risk management. Maintenance practices and strategies are selected to ensure that engines operate reliably, avoid costly downtime, maintain safety standards, and achieve their intended operational lifecycle [18]. By combining well-defined maintenance practices with strategic decision-making, marine and industrial diesel engines can meet reliability requirements and contribute to efficient and smooth operations [11]. In the last few years, the shipping industry has adjusted to the international standards and recommendations of the International Maritime Organisation (IMO) and other maritime regulations [10].

Strategic maintenance and practices, more specifically preventive and predictive maintenance play a vital role in improving the reliability of both marine and industrial diesel engines. These practices are designed to proactively address potential issues, minimize unplanned downtime, and extend the operational life of the engines. Preventive maintenance involves scheduled routine inspections, servicing, and component replacements based on manufacturer recommendations and industry best practices. These maintenance activities address wear and tear before they escalate into more severe problems. Predictive maintenance involves using data-driven insights and real-time monitoring to predict when maintenance is needed. By analyzing performance data and trends, operators can take corrective actions before failures occur. Scheduled inspections, component replacements, and proactive interventions collectively prevent excessive wear and deterioration of engine components. Strategic maintenance practices extend the operational lifecycle of marine and industrial diesel engines by addressing minor issues before they develop, reducing the frequency of major overhauls, and maintaining engine performance at stable levels.

Marine vessels and industrial applications heavily rely on the consistent availability of engines. By minimizing the downtime caused by different breakdowns, these practices directly enhance the reliability of both engine types.

In marine applications, accessibility to different components for regular maintenance can be challenging due to the compact and confined spaces on vessels. While industrial engines may offer more accessible components, regular maintenance is crucial to prevent unexpected failures and maintain optimal performance.

5 Methodology of the reliability calculations

In this study, we will rely on the data from the OREDA (Offshore REliability DAta) handbook [19], which is the most comprehensive resource of reliability data in the maritime domain for reliability engineering and risk assessment. The data in the OREDA handbook is collected from various sources, including data from offshore installations, and is used by engineers and researchers to assess the reliability of equipment and systems used in offshore operations [9]. The OREDA handbook includes data on failure rates, repair rates, and other reliability-related parameters for various offshore equipment, such as pumps, valves, electrical systems, control systems, and more [19]. The handbook includes reliability data from offshore drilling and production. Unfortunately, obtaining such data for ship installations has proven to be exceedingly challenging. Consequently, the only possible solution for many reliability studies is to use a data set from OREDA. However, in our research, offshore installations expose equipment to conditions mutually relevant to both marine and industrial engines. The OREDA data presents a valuable opportunity to perform reliability analysis of both marine and industrial engines.

OREDA does not differentiate between independent and dependent failures; Independent failures in diesel engine systems occur without any direct influence from other failures. These failures are random and unrelated to the functioning or failure of other components, while dependent failures are those where the failure of one component influences or causes the failure of another component. Moreover, no alternative source of failure rate data for dependent failures has been identified. Jones [20] suggests that around 10% of failures are dependent, although the method of determining this percentage remains unclear. In order to explore the impact of even minor numbers of dependent failures on reliability, we assume in our reliability calculations that 10% of the failures considered in these scenarios are dependent. We also assumed the failure rates are exponentially distributed during the useful life phase, which means our calculation focuses on the constant part of the bath-tube curve. In addition, all the data from the OREDA handbook are measured per 10^6 hours of aggregated time in service [19].

5.1 Important metrics used for the reliability calculations

Reliability calculation for individual diesel engine components involves determining the probability that each component will perform its intended function without failure over a specified period. The specific reliability calculation method will depend on the type of component and the available data. Various mathematical models and equations could be used to calculate the reliability function depending on the component type and the available data [1]. The following two concepts are integral in the reliability analysis of diesel engine components:

1. Mean Time to Failure (*MTTF*)

MTTF is the average time expected until the first failure of a piece of equipment or a system. It's a statistical measure typically used for non-repairable systems or where repair is not economically feasible. *MTTF* (1) is often used in systems with redundant components, where it helps determine the overall system reliability.

$$MTTF = 1/\lambda \qquad [h] \qquad (1)$$

where: λ is the failure rate of the component.

2. Exponential Distribution

The exponential distribution is commonly used to model the failure rate behavior of components or systems that exhibit a constant failure rate over time. It assumes that failures occur randomly and are unrelated to previous failures. The failure rate (λ) represents the rate at which failures occur and remains constant throughout the component's life. The reliability function (2) for components following an exponential distribution can be calculated using the following equation:

$$R(t) = exp(-\lambda t) \qquad (2)$$

where: $R(t)$ is the reliability at time t;
λ is the failure rate parameter.

The failure rate parameter can be estimated using historical failure data or testing and analysis. The exponential distribution assumes independence between failures, which may not be valid when failures depend on previous events or conditions. Therefore, it's crucial to evaluate the appropriateness of the exponential distribution and consider alternative distributions or models if necessary.

6 Case studies for different heat exchanger models at offshore installations

Diesel engine heat exchangers are selected as the equipment unit for analysis in this study because they are one of the distinguishing units between marine diesel engines and industrial diesel engines. Heat exchangers are a vital component that transfers heat from the engine coolant to a separate cooling fluid; marine engines usually use seawater. It helps regulate the temperature of the coolant by dissipating excess heat. Industrial diesel engines also commonly use heat exchangers to maintain optimal operating temperatures.

There are several types of heat exchangers used for both marine diesel engines and industrial diesel engines. The specific type of heat exchanger utilized can vary based on engine design, cooling system requirements, and space limitations. A few common types are Fin fan heat exchangers, Plate heat exchangers, and Shell & Tube heat exchangers. The failure rate characteristics of heat exchangers can vary depending on design, material quality, maintenance practices, operating conditions, and the engine's environment. When properly maintained, heat exchangers generally have a relatively constant failure rate throughout their operational life.

The following results demonstrate the failure rates at critical failure modes for marine and industrial engines, in the case of different heat exchanger models, Mean Time to Failure values, and reliability function, in addition to the possible applications in marine diesel engines and industrial diesel engines. Also, the following results show the influence of dependent and independent failures on the reliability function by assuming 10% of the failures caused by dependent reasons and comparing these results to the 100% independent failures. In the context of heat exchangers in diesel engines, understanding whether a failure is independent, or dependent is crucial for designing robust systems. Independent failures may be addressed through regular maintenance and monitoring of individual components. On the other hand, dependent failures might require additional safeguards, such as redundant components or backup systems, to prevent failures that could compromise the overall reliability and performance of the diesel engine.

The possible independent and dependent failure in the case of the heat exchangers can be the following:

1. Independent failures in heat exchangers: For example, the degradation of a heat exchanger's fin due to corrosion over time. This is an independent failure as it occurs without being directly influenced by the state of other components. It may lead to reduced heat transfer efficiency but does not cause failures in other parts of the system.

2. Dependent failures in heat exchangers: For example, the failure of a coolant pump in the engine cooling system leads to insufficient coolant flow through the heat exchanger. This dependent failure can result in increased temperatures in the engine, potentially causing other components, such as gaskets or seals, to fail due to overheating.

6.1 First case study: Fin fan heat exchangers

Fin fan heat exchangers, also known as air-cooled or finned-tube heat exchangers, are widely used in various industries, including marine and industrial applications. These heat exchangers are crucial in dissipating heat from process fluid to the surrounding air through finned tubes and fans. They are commonly used when water sources are rare or when processed fluids need to be cooled without direct contact with cooling water.

In Table 3, we used failure rate (λ_i) values at different failure modes, which have been collected in the OREDRA handbook from empirical observations on offshore platforms. These failure rate modes are Insufficient heat transfer, Minor in-service problems, and Parameter deviation. The term "parameter deviation" refers to a situation where one or more critical parameters deviate from their expected or designed values, leading to a potential failure or degradation in the performance of the heat exchanger. These parameters could include factors such as temperature, pressure, flow rates, or other operational conditions. These failure rate values are used to calculate *MTTF* by applying equation (1), and this analysis is conducted in two cases: a) all failures are evolved due to independent factors; b) only 90% of failures are evolved due to independent factors and 10% are evolved due to dependent factors. This comparison allows us to evaluate the impact of sustaining the optimal performance of all equipment within the system.

Table 3 Failure rate and MTTF results for Fin fan heat exchanger [19]

Critical Failure modes	a) λ_i [h^{-1}]	***MTTF*** [h]		b) ***90%*** λ_i [h^{-1}]	***MTTF*** [h]
1. Insufficient heat transfer	$\lambda_1 = 6.84 \cdot 10^{-6}$	$146.198 \cdot 10^{+3}$		$6.156 \cdot 10^{-6}$	$162.443 \cdot 10^{+3}$
2. Minor in-service problems	$\lambda_2 = 3.42 \cdot 10^{-6}$	$292.397 \cdot 10^{+3}$		$3.078 \cdot 10^{-6}$	$324.886 \cdot 10^{+3}$
3. Parameter deviation	$\lambda_3 = 3.42 \cdot 10^{-6}$	$292.397 \cdot 10^{+3}$		$3.078 \cdot 10^{-6}$	$324.886 \cdot 10^{+3}$
4. Other*	$\lambda_4 = 3.42 \cdot 10^{-6}$	$292.397 \cdot 10^{+3}$		$3.078 \cdot 10^{-6}$	$324.886 \cdot 10^{+3}$

**Other includes (Abnormal instrument reading, Internal leakage, Plugged/Choked, and Structural deficiency).*

The results in Table 3 illustrate how even a small impact, such as 10% from other equipment inefficiencies, affects the failure rate. This influence manifests as a reduction in the service time of the heat exchanger, ranging from a minimum of (*MTTF* = 16,245 hours) to a maximum of (*MTTF* = 32,489 hours); (these numbers represent the difference in *MTTF* values before and after removing 10% of the failure rate λ_i), highlighting the potential variability in the operational lifecycle due to this impact. Table 4 shows reliability calculation in the cases of 4 scenarios: 1.) Insufficient heat transfer (mainly related to marine applications); 2.) Parameter deviation (mainly related to industrial applications); and Cumulative failure rates in both cases; 3.) 90% of failures are evolved due to independent factors, and 4.) all failures are developed due to independent factors. The reliability values in these four scenarios are calculated by equation (2). These results provide the reliability of the heat exchanger at different calendar times (t_I = 2500 [h], t_{II} = 5000 [h], t_{III} = 7500 [h], and t_{IV} = 10000 [h]).

Table 4 Reliability calculation at different calendar times t_i

Fin fan heat exchanger	**Reliability of the heat exchanger**			
	t_I = **2500** [h]	t_{II} = **5000** [h]	t_{III} = **7500** [h]	t_{IV} = **10000** [h]
Insufficient heat transfer	98.3	96.63	94.99	93.38
Parameter deviation	99.14	98.30	97.46	96.63
$\Sigma \lambda_i$ [h^{-1}]	95.81	91.80	87.96	84.28
Σ 90% λ_i [h^{-1}]	96.22	92.59	89.09	85.73

The results in Table 4 illustrate the importance of understanding different failure rates and their impact on the reliability of fin fan heat exchangers in various applications, including marine and industrial diesel engines. The differential failure modes experienced by marine and industrial diesel engines can be attributed to several critical factors, including the distinct operating environments, cooling fluids, and operational requirements. As time passes, the reliability of the heat exchanger decreases. This is noticeable from the decreasing values in the "Reliability of the heat exchanger" columns. Figure 1 shows the fin fan heat exchangers' reliability function at different failure modes, demonstrating the relation between reliability function *R(t)* and time.

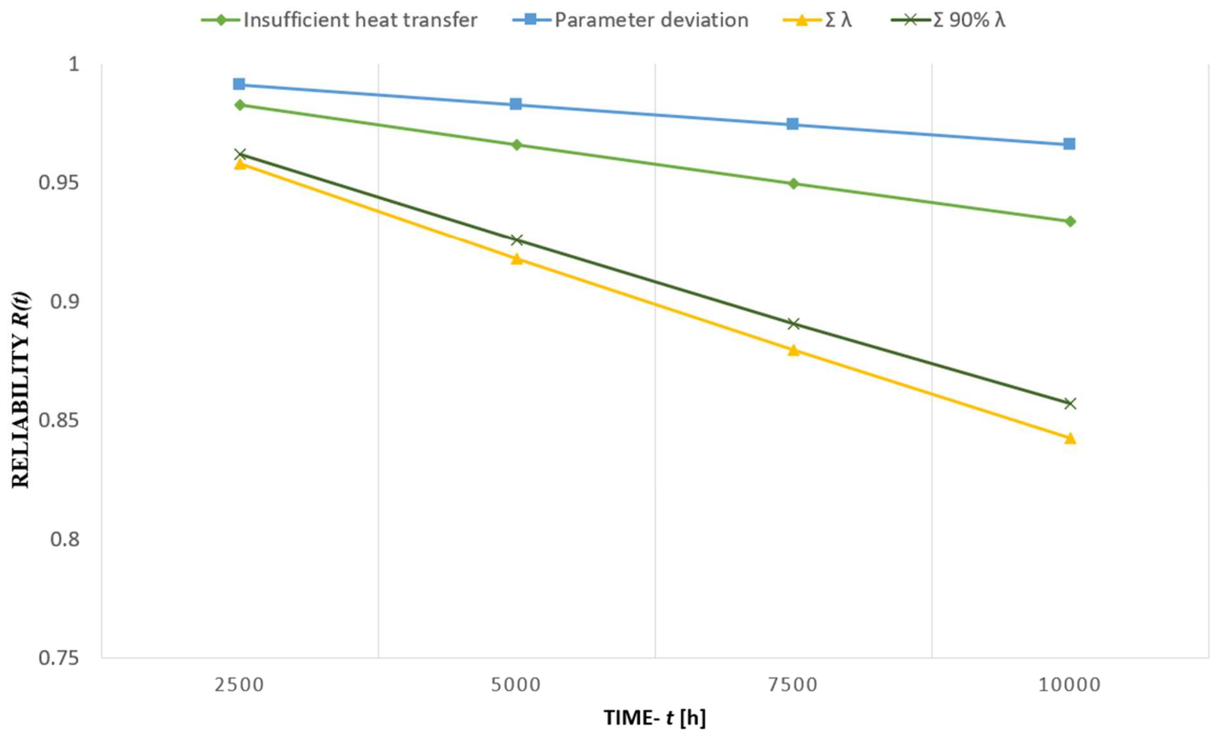

Figure 1 Reliability function at different failure modes (Fin fan heat exchangers)

Cumulative failure rates ($\Sigma \lambda i$) represent the combined failure rates of all identified failure modes (yellow line in Figure 1). It provides a measure of the overall reliability (*R(t)*) of the heat exchanger. As time progresses, the cumulative failure rate increases, which increases the probability of failure. Tables 3-4, and Figure 1 show how even a small change in the failure rate can significantly affect both the cumulative failure rate and *MTTF*. For instance, if the failure rate for "Insufficient heat transfer" were slightly higher or lower, it would have a notable

Volume: 11 2024 Issue: 2 Pages: 325-337 ISSN 1339-5629

impact on the overall reliability and *MTTF* of the heat exchanger. Insufficient heat transfer (green line in Figure 1) in marine diesel engines is often related to fouling and corrosion caused by a corrosive nature like seawater, which links this type of failure rate primarily to marine applications.

Industrial diesel engines typically operate in controlled environments with less exposure to corrosive elements. Therefore, the corrosion resistance challenge is less severe in industrial applications. Industrial engines typically have complex control systems to maintain temperature and flow rate parameters. Errors or malfunctions in these systems can lead to parameter deviation (blue line in Figure 1), affecting heat exchanger performance.

Heat exchangers' failure modes and rates can vary between marine and industrial applications. The specific failure modes and their frequencies can be influenced by factors such as the type of fluids being cooled, the operating conditions, and the maintenance practices. For example, marine engines may be more susceptible to structural deficiencies due to the harsh environment. In contrast, industrial engines might face more minor in-service problems related to processing fluids. Marine heat exchangers must be highly resistant to corrosion caused by saltwater. This necessitates using specialized materials and coatings to protect the fine tubes and other components from deterioration. While industrial engines may not face the same level of corrosion as marine engines, they still require corrosion-resistant materials, especially when dealing with chemically aggressive fluids.

6.2 *Second case study: Plated heat exchangers*

Plated heat exchangers are valuable marine and industrial diesel engine components. These heat exchangers are vital in managing heat and maintaining efficient engine operation, whether for cooling systems, heat recovery, or other applications. The plates are typically made of materials such as stainless steel or titanium to ensure efficient heat transfer and corrosion resistance.

In Table 5, we used failure rate values at different failure modes, which have been collected in the OREDRA handbook [20] from empirical observations on offshore platforms. The critical failure modes are external leakage - Process medium, external leakage - Utility medium, and parameter deviation. The failure rate values are used to calculate *MTTF* by applying equation (1), and this analysis is conducted in two cases: a.) all failures are evolved due to internal factors; b.) only 90% of failures are developed due to internal factors, and 10% are developed due to external factors.

Table 5 Failure rate and MTTF results for Plated heat exchanger [19]

Critical failure modes	**a)** λ_i $[h^{-1}]$	***MTTF*** [h]		**b)** ***90%*** λ_i $[h^{-1}]$	***MTTF*** [h]
External leakage - Process medium	$\lambda_1 = 9.49 \cdot 10^{-6}$	$105.374 \cdot 10^{+3}$		$8.541 \cdot 10^{-6}$	$117.082 \cdot 10^{+3}$
External leakage - Utility medium	$\lambda_2 = 4.34 \cdot 10^{-6}$	$230.414 \cdot 10^{+3}$		$3.906 \cdot 10^{-6}$	$256.016 \cdot 10^{+3}$
Parameter deviation	$\lambda_3 = 4.34 \cdot 10^{-6}$	$230.414 \cdot 10^{+3}$		$3.906 \cdot 10^{-6}$	$256.016 \cdot 10^{+3}$

The results in Table 5 illustrate how even a small impact, such as 10% from other equipment inefficiencies, affects the failure rate. This influence manifests as a reduction in the service time of the heat exchanger, ranging from a minimum of (*MTTF* = 11,708 hours) to a maximum of *MTTF* = 25,602 hours); (These numbers represent the difference in *MTTF* values before and after removing 10% of the failure rate λ_i), highlighting the potential variability in the operational lifecycle due to this impact. Table 6 shows reliability calculation in the case of 4 scenarios, which are the following: 1.) External leakage - Process medium; 2.) External leakage - Utility medium; Cumulative failure rates in two cases: 3.) 90% of failures are evolved due to independent factors; furthermore, 4.) Cumulative failure rates in case of all the failures are evolved due to independent factors. The reliability values in these four scenarios are calculated by equation (2). These results provide the reliability of the heat exchanger at different calendar times (t_I = 2500 [h], t_{II} = 5000 [h], t_{III} = 7500 [h], and t_{IV} = 10000 [h]).

Table 6 Reliability calculation at different calendar times t_i

Plate heat exchangers	**Reliability of the heat exchanger**			
	t_I **= 2500** [h]	t_{II} **= 5000** [h]	t_{III} **= 7500** [h]	t_{IV} **= 10000** [h]
External leakage - Process medium	97.65	95.36	93.12	90.94
External leakage - Utility medium	98.92	97.85	96.79	95.75
$\Sigma \lambda_i$ $[h^{-1}]$	95.55	91.31	87.26	83.38
Σ 90% λ_i $[h^{-1}]$	95.99	92.14	88.45	84.91

The results in Table 6 illustrate the importance of understanding different failure rates and their impact on the reliability of plated heat exchangers in various applications. The differential failure modes experienced by marine and industrial diesel engines can be attributed to several critical factors, including the distinct operating environments, cooling fluids, and operational requirements. As time passes, the reliability of the heat exchanger decreases. Figure 2 shows the reliability function of plated heat exchangers at different failure modes, demonstrating the relation between reliability function *R(t)* and time.

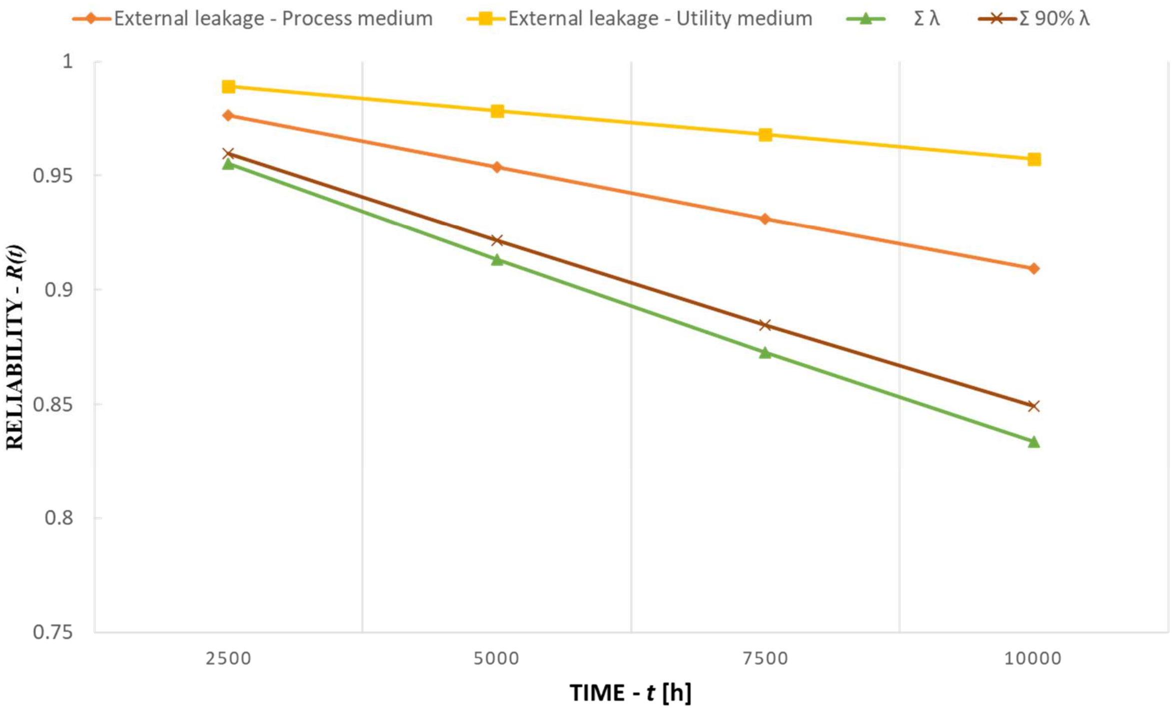

Figure 2 Reliability function at different failure modes (Plate heat exchangers)

The failure modes demonstrated in Figure 2, Table 5, and Table 6 include "External leakage - Process medium; (orange line in Figure 2)" and "External leakage - Utility medium; (yellow line in Figure 2)" are critical for both marine and industrial applications in a different perspective. Leakage can lead to the mixing of fluids, efficiency loss, and potential damage. "Parameter deviation" is another failure mode listed, which indicates that deviations in operating parameters (e.g., temperature, pressure) can impact heat exchanger performance. This is a common challenge in both marine and industrial applications. It also demonstrates that the reliability of plated heat exchangers decreases over time. This indicates that as the heat exchanger operates for longer durations, its reliability decreases, and the probability of experiencing a failure increases, which requires proactive maintenance to extend *MTTF*. Cumulative failure rates ($\Sigma \lambda_i$) represent the combined failure rates of all identified failure modes (green line in Figure 2). It provides a measure of the overall reliability ($R(t)$) of the heat exchanger. As time progresses, the cumulative failure rate increases, which increases the probability of failure.

In marine applications, accessibility to heat exchangers for maintenance can be challenging due to the limited space on vessels. Industrial engines may offer more accessible heat exchangers, making maintenance easier. However, Industrial engines may deal with a broader range of fluid properties, including chemicals and contaminants, which can affect the performance and longevity of plated heat exchangers. Monitoring and maintenance strategies must be adapted accordingly.

6.3 Third case study: Shell & Tube heat exchangers

Shell & Tube heat exchangers are another type commonly used in marine and industrial diesel engines to facilitate heat transfer between fluids. These heat exchangers help regulate the temperature of the engine coolant by transferring heat from the coolant to a separate cooling medium, such as seawater, which prevents engine overheating and ensures efficient operation. Shell and tube heat exchangers are durable and can withstand harsh operating environments, making them suitable for marine and industrial applications. In addition, this type of heat exchanger is designed for easy inspection and cleaning, with removable tubes that facilitate maintenance activities.

In Table 7, we used failure rate values at different failure modes, which have been collected in the OREDRA handbook from empirical observations on offshore platforms. The critical failure modes are 1.) Abnormal instrument reading, 2.) External leakage-process medium, 3.) Parameter deviation, and 4.) Structural deficiency. These failure rate values are used to calculate *MTTF* by applying equation (1), and this analysis is conducted in two cases: a.) All failures are evolved due to internal factors. b.) Only 90% of failures are developed due to internal factors, and 10% are developed due to external factors. This comparison allows us to evaluate the impact of sustaining the optimal performance of all equipment within the system.

Table 7 Failure rate and MTTF results for Shell & tube heat exchanger [19]

Critical failure modes	**a)** λ_i [h^{-1}]	***MTTF*** [h]		**b)** ***90%*** λ_i [h^{-1}]	***MTTF*** [h]
Abnormal instrument reading	$\lambda_1 = 17.39 \cdot 10^{-6}$	$57.504 \cdot 10^{+3}$		$15.651 \cdot 10^{-6}$	$63.893 \cdot 10^{+3}$
External leakage – Process medium	$\lambda_2 = 7.67 \cdot 10^{-6}$	$130.378 \cdot 10^{+3}$		$6.903 \cdot 10^{-6}$	$144.864 \cdot 10^{+3}$
Parameter deviation	$\lambda_3 = 4.49 \cdot 10^{-6}$	$222.717 \cdot 10^{+3}$		$4.041 \cdot 10^{-6}$	$247.463 \cdot 10^{+3}$
Structural deficiency	$\lambda_4 = 8.07 \cdot 10^{-6}$	$123.915 \cdot 10^{+3}$		$7.263 \cdot 10^{-6}$	$137.684 \cdot 10^{+3}$

The results in Table 7 illustrate how even a small impact, such as 10% from other equipment inefficiencies, affects the failure rate. This influence manifests as a reduction in the service time of the heat exchanger, ranging from a minimum of (*MTTF* = 6,389 hours) to a maximum of (*MTTF* = 13,769 hours); (These numbers represent the difference in *MTTF* values before and after removing 10% of the failure rate λ_i), highlighting the potential variability in the operational lifecycle due to this impact. Table 8 shows reliability calculation in the case of 6 scenarios: 1.) Abnormal instrument reading; 2.) External leakage - Process medium; 3.) Parameter deviation; 4.) Structural deficiency; 5.) Cumulative failure rates in the case of 90% of failures developed due to independent factors; furthermore, 6.) Cumulative failure rates in case of all failures are developed due to independent factors. The reliability values in these six scenarios are calculated by equation (2). These results provide the reliability of the heat exchanger at different calendar times (t_I = 2500 [h], t_{II} = 5000 [h], t_{III} = 7500 [h], and t_{IV} = 10000 [h]).

Table 8 Reliability calculation at different calendar times t_i

Shell & Tube heat exchanger	**Reliability of the heat exchanger**			
	t_I **= 2500** [h]	t_{II} **= 5000** [h]	t_{III} **= 7500** [h]	t_{IV} **= 10000** [h]
Abnormal instrument reading	95.74	91.67	87.77	84.03
External leakage - Process medium	98.10	96.23	94.40	92.61
Parameter deviation	98.88	97.78	96.68	95.60
Structural deficiency	98.00	96.04	94.12	92.24
$\Sigma\, \lambda i$ [h^{-1}]	97.85	95.75	93.70	91.69
Σ 90% λi [h^{-1}]	98.06	96.17	94.31	92.49

The results in Table 8 illustrate the importance of understanding different failure rates and their impact on the reliability of shell and tube heat exchangers in various applications, including marine and industrial diesel engines. The differential failure modes experienced by marine and industrial diesel engines can be attributed to several critical factors, including the distinct operating environments, cooling fluids, and operational requirements. As time passes, the reliability of the heat exchanger decreases. This is noticeable from the decreasing values in the "Reliability of the heat exchanger" columns. Figure 3 shows the reliability function of Shell & Tube heat exchangers at different failure modes, demonstrating the relation between reliability function *R(t)* and time.

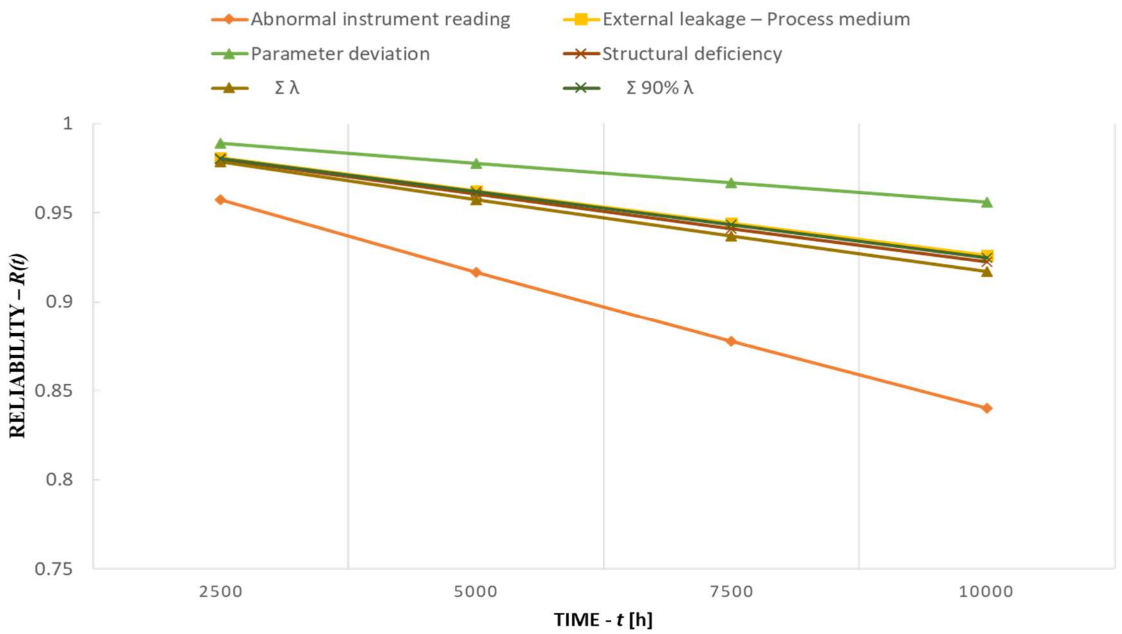

Figure 3 Reliability function at different failure modes (Shell & Tube heat exchangers)

The provided data in Figure 3, Tables 7-8 shows several critical failure modes and their associated failure rates (λ). "External leakage – Process medium" and "Parameter deviation" are listed as failure modes, similar to the challenges faced by plate and fine tube heat exchangers. In addition, "Structural deficiency" is another failure mode, indicating potential structural issues in the heat exchanger. This can be a concern, especially in marine applications where the equipment may be subjected to vibrations and extreme conditions. Table 8 shows the reliability of the shell and tube heat exchanger at different calendar times. Like the other heat exchanger types, shell and tube heat exchangers experience decreased reliability over time. Proper maintenance practices are essential to extend the Mean Time Between Failures (*MTTF*) and ensure efficient operation. Cumulative failure rates ($\Sigma\ \lambda_i$) represent the combined failure rates of all identified failure modes (brown line in Figure 3). It provides a measure of the overall reliability ($R(t)$) of the heat exchanger. As time progresses, the cumulative failure rate increases, which increases the probability of failure. The following chart demonstrates a Comparison of *MTTF* and Reliability in the case of the three heat exchanger types.

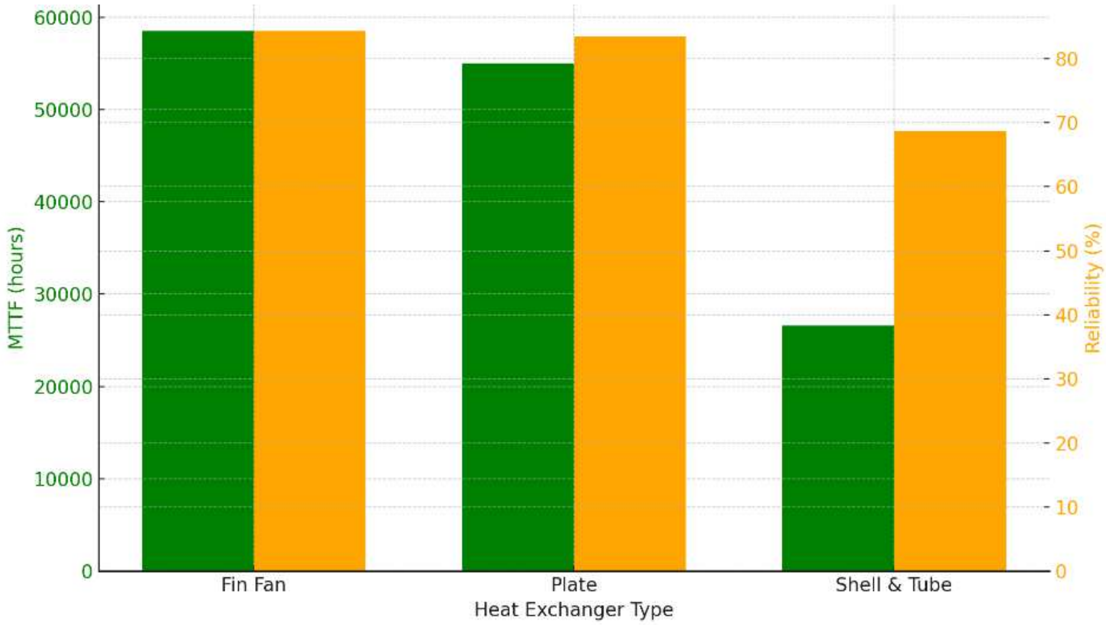

Figure 4 Comparison of MTTF and Reliability in the case of the three heat exchanger types

In Figure 4, two key parameters, *MTTF* and Reliability, are compared for the three types of heat exchangers (Fin Fan, Plate, and Shell & Tube).

1. *MTTF* is represented in hours. This parameter indicates the average operational time before a failure is expected. The higher the *MTTF*, the longer the component is expected to function without failure. In this Figure, it is shown on the left *Y*-axis in green.

2. Reliability is expressed as a percentage. This reflects the probability of a heat exchanger operating without failure for a specific duration (in this context at t_{IV} = 10000 hours). Higher reliability percentages indicate a greater likelihood of the component functioning correctly over time. It is displayed on the right *Y*-axis in orange.

By comparing these two parameters, we can see how each type of heat exchanger performs in terms of both longevity (*MTTF*) and consistent performance (*Reliability*) over time. This comparative analysis aids in understanding the strengths and weaknesses of each heat exchanger type in practical applications.

In summary, while these heat exchangers are used in marine and industrial diesel engines to manage temperature and heat transfer, the specific challenges and operating conditions can lead to differences in the choice of materials, maintenance practices, and strategies for addressing failure modes. Our research contributes to a deeper understanding of diesel engine reliability in marine and industrial contexts. We demonstrated that while both engine types share some common reliability challenges, each also faces unique conditions that require specific strategies and solutions. The study offers valuable insights into three types of heat exchangers, enhancing our understanding of diesel engine components. It provides a foundation for further research and development, aiming to improve the performance and safety of these critical engines in their respective sectors.

7 Conclusions

This paper has explored the reliability requirements for both marine and industrial diesel engines, emphasizing their main roles in marine vessels and various industrial applications. The comparative analysis conducted throughout this study has shed light on several vital factors that distinctly influence the reliability of each engine type, thereby offering valuable insights into their unique challenges and considerations. Our comprehensive study on the reliability of different heat exchanger models used in marine and industrial diesel engines focused on Fin fan heat exchangers, Plate heat exchangers, and Shell & Tube heat exchangers, assessing their failure rates, *MTTF*, and the impact of independent and dependent failures on their reliability.

The study reveals distinct failure modes in heat exchangers, including insufficient heat transfer, external leakage, parameter deviation, and structural deficiencies, which affect marine and industrial diesel engines differently. In marine engines, which frequently use seawater in heat exchangers, the challenges of corrosion and fouling are prominent. Conversely, industrial engines primarily face issues related to system controls and parameters, typically operating in less corrosive environments. A significant result is a 10% alteration in failure rates, attributable to equipment inefficiencies, impacting the Mean Time to Failure (*MTTF*), pointing to the necessity for robust design and diligent maintenance strategies. Effective management of independent failures such as corrosion can be achieved through routine maintenance, whereas dependent failures, leading to conditions such as overheating, require more sophisticated solutions, including the incorporation of redundancy and backup systems to maintain overall engine reliability. The selection of materials and the design of heat exchangers are especially crucial in marine applications where corrosion resistance is a key consideration. Furthermore, the study underscores the importance of maintenance and monitoring, especially in industrial settings, where proactive maintenance strategies are fundamental to enhancing reliability and prolonging *MTTF*.

In summary, this study offers a comprehensive analysis of heat exchanger reliability in marine and industrial diesel engines. It highlights the need to consider a spectrum of factors, from environmental conditions to specific failure modes, maintenance practices, and material selections. These insights are vital for improving the operational efficiency and longevity of heat exchangers, providing valuable guidance for the design and operation of diesel engines across varied industrial and marine applications.

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Review process

Single-blind peer review process.