ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Navigating Halal Compliance in the Maritime Industry: A Systematic Analysis of Challenges and Best Practices

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Abstract – Halal food management within the maritime industry presents unique challenges due to the complex global supply chain, inconsistent halal certification standards, and risks of cross-contamination. Despite the growing demand for halal-certified food among Muslim seafarers and passengers, maritime operators face significant hurdles in ensuring compliance with halal regulations. This study conducts a systematic meta-analysis using the PRISMA framework to identify the key challenges, regulatory gaps, and best practices in maritime halal food logistics. The findings highlight the need for harmonised certification processes, improved traceability mechanisms, and the integration of advanced technologies such as blockchain and AI to enhance compliance. The study concludes by proposing a structured framework to optimise halal food management in maritime operations.

Keywords: blockchain technology, certification standards, halal food logistics, maritime industry, supply chain management

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1.0 INTRODUCTION

Halal food management is an essential component of the global food industry, ensuring that food production, transportation, and consumption adhere to Islamic principles. While various sectors have developed robust halal food supply chains, the maritime industry remains an underexplored domain despite its critical role in global food transportation. The complexity of the maritime supply chain, involving multiple intermediaries and ports with varying halal certification standards, presents significant challenges in maintaining halal food integrity (Gezgin et al., 2024). Additionally, cross-contamination risks, improper segregation of Halal and non-Halal goods, combined with insufficient personnel training, increase the risk of cross-contamination and complicate compliance efforts (Ali et al., 2021).

The maritime industry operates under international regulations such as those set by the International Maritime Organisation (IMO) and the Maritime Labour Convention (MLC), which emphasise hygiene and food safety but lack specific guidelines for halal compliance (International Maritime Organization (IMO), 2022). This study aims to address these gaps by systematically analysing existing literature on halal food logistics within maritime operations. By leveraging the PRISMA framework, this research identifies key challenges, evaluates existing regulatory measures, and proposes best practices to ensure effective halal food management at sea. The study further explores technological advancements such as blockchain and AI-driven monitoring systems as potential solutions to enhance transparency, traceability, and compliance in halal food logistics (Sunmola et al., 2025).

2.0 LITERATURE REVIEW

2.1 Halal Food Management in the Maritime Industry

Ensuring halal integrity throughout the maritime supply chain requires adherence to strict logistical protocols. Key measures include utilising halal-certified storage and goods facilities, maintaining clear segregation between halal and non-halal goods, and implementing standardised halal compliance practices (LBB International, 2024). Companies like Nippon Express and Yusen Logistics have adopted halal logistics solutions, including dedicated storage facilities and certification programs, to mitigate risks of cross-contamination (Nippon Express, 2025; Yusen Logistics, 2025).

The IMO and MLC provide general guidelines on food safety and hygiene aboard ships, but their lack of specificity regarding halal compliance necessitates additional measures. Best practices include the development of onboard halal food policies, crew training programs, and regular halal compliance audits. Additionally, sourcing food supplies from certified halal providers and integrating digital certification systems can improve transparency and regulatory adherence (International Labour Organization (ILO), 2022).

2.2 Challenges in Halal Food Logistics

The primary challenges in maritime Halal food logistics include cross-contamination risks, inconsistent certification standards, and limited traceability mechanisms. Inadequate segregation protocols in ports and onboard vessels heighten the risk of contamination, while the absence of a unified global Halal certification standard leads to discrepancies in compliance requirements across different regions. These inconsistencies complicate shipping operations and pose regulatory challenges for maritime food suppliers (Abd Aziz et al., 2024).

To mitigate these risks, traceability systems are essential in ensuring the integrity of Halal food throughout transportation. Blockchain technology and AI-driven monitoring provide potential solutions by establishing a secure and verifiable record of product movement and certification status. These digital solutions can bridge regulatory gaps and enhance compliance in maritime food logistics, ensuring greater transparency and efficiency (Masudin et al., 2022; Sunmola et al., 2025).

2.3 Regulatory Frameworks and Standards

Regulatory inconsistencies pose a significant challenge in maritime halal food management. International organisations such as the Islamic Development Bank (IsDB) and the Standards and Metrology Institute for Islamic Countries (SMIIC) have established halal food standards, but their implementation remains uneven across maritime operations (Wace, 2018). Different countries enforce varying certification schemes, leading to logistical obstacles for halal food transportation.

To standardise halal compliance, policymakers must work towards harmonising global certification processes and establishing clear halal-specific protocols in ports. The adoption of international halal standards can improve consistency and facilitate smoother operations in maritime food logistics. Furthermore, enhanced regulatory oversight and increased collaboration between certification bodies can strengthen the halal supply chain.

3.0 RESEARCH METHODOLOGY

This study employs a systematic review methodology using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a rigorous and comprehensive analysis of halal food management in the maritime industry. The research follows four key phases: identification, screening, eligibility, and inclusion.

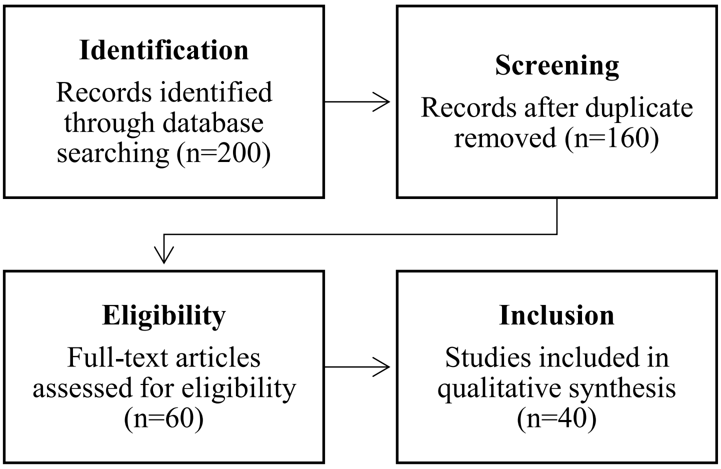

Figure 1: PRISMA Flow Diagram will be inserted here to illustrate the identification, screening, eligibility, and inclusion process

1. Identification: A comprehensive literature search was conducted using databases such as Scopus, Web of Science, and Google Scholar. The search utilised keywords such as "halal food logistics," "maritime industry halal compliance," "halal certification in shipping," and "blockchain in halal logistics." Only peer-reviewed journal articles and industry reports published between 2022 and 2025 were considered. Articles prior to 2022 were excluded to ensure the review reflects the most recent developments in halal logistics, especially considering the rapid technological advancements and regulatory changes in recent years.

2. Screening: Duplicates and irrelevant studies were removed. Studies that did not focus on halal food in maritime logistics were excluded.

3. Eligibility: Full-text articles were assessed for relevance based on predefined inclusion criteria:

   (a) relevance to halal food logistics

   (b) application to maritime industry operations, and

   (c) inclusion of regulatory, technological, or operational perspectives. Studies lacking empirical or theoretical relevance were excluded.

4. Inclusion: A total of 40 studies met the criteria and were included in the review. The selected studies were analysed to extract key themes related to challenges, regulatory frameworks, and best practices in halal food management within maritime logistics.

4.0 FINDINGS AND DISCUSSION

The review of 40 selected articles revealed that approximately one-third addressed regulatory fragmentation, another one-third discussed supply chain inefficiencies, and the remainder focused on technological adoption challenges. This distribution underscores the need for balanced attention to all three aspects.

The meta-analysis highlights three major challenges in Halal food logistics: regulatory fragmentation, supply chain inefficiencies, and limited technological adoption. The lack of standardised Halal-specific handling protocols at ports and onboard vessels increases the risk of non-compliance and cross-contamination (Masudin et al., 2022). Additionally, varying certification standards across jurisdictions create operational hurdles for shipping companies, requiring extra layers of verification.

The study also finds that emerging technologies such as blockchain and AI present viable solutions to enhance traceability and regulatory adherence. These innovations not only help in maintaining an unalterable record of Halal certification but also streamline real-time tracking of food products throughout maritime logistics networks. Furthermore, structured Halal compliance training for maritime personnel is essential to strengthen best practices and mitigate operational risks.

5.0 CONCLUSION

Ensuring the integrity of Halal food in maritime logistics requires a holistic approach that addresses regulatory inconsistencies, supply chain vulnerabilities, and technological limitations. This study underscores the urgent need for harmonised Halal certification standards, coupled with improved traceability systems to safeguard Halal food integrity across international shipping routes.

The integration of blockchain and AI technologies offers a promising pathway to enhance compliance, reduce operational inefficiencies, and strengthen food security measures. Future research should focus on developing standardised international Halal regulations for maritime operations, exploring the feasibility of implementing blockchain-driven solutions, and identifying cost-effective strategies for widespread adoption. Collaborative efforts among policymakers, industry stakeholders, and certification bodies are crucial to establishing a seamless and globally recognised Halal food supply chain in the maritime sector. This aligns with findings from Masudin et al. (2022) on traceability systems and Sunmola et al. (2025) on AI-driven halal compliance frameworks, further supporting the feasibility of the proposed framework.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Material Selection for Marine Heat Exchangers: A Comprehensive Review of Thermal and Corrosion Performance

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Abstract – This journal article delves into the realm of heat exchanger materials, presenting a comprehensive analysis of their influence on thermal efficiency and overall performance. Covering an array of materials, including metals, alloys, polymers, and composites, the study investigates their thermal conductivity, corrosion resistance, and mechanical characteristics within the context of heat exchange applications. By synthesising existing literature, the article offers valuable insights for engineers and researchers grappling with material selection for various heat exchanger scenarios. The examination of factors such as operating conditions, cost considerations, and sustainability aids in navigating the complex decision-making process. This work seeks to provide a practical guide for optimising heat exchanger design, ultimately contributing to advancements in efficiency and durability across diverse industrial settings.

Keywords: Heat Exchanger, Heat Transfer, Plate Heat

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1.0 INTRODUCTION

Heat exchangers are critical components in a variety of industrial systems, including marine applications, where they facilitate the efficient transfer of thermal energy between fluids. In maritime operations, these devices are tasked with managing extreme environmental conditions, including high salinity, fluctuating temperatures, and corrosive seawater exposure. Plate heat exchangers (PHEs) are increasingly favoured in marine applications due to their compact design, efficient heat transfer capabilities, and ability to withstand the rigorous demands of maritime environments (Zhang et al., 2019). The material selection for these systems, particularly the plates and gaskets, is paramount to ensure long-term durability, optimal heat transfer, and resistance to thermal stress and corrosion.

A significant challenge in marine heat exchanger design is identifying materials that offer an ideal balance of thermal efficiency and corrosion resistance. Materials such as titanium, stainless steel, and specialised alloys are commonly chosen for their strength and resistance to seawater corrosion (Pandya et al., 2020). However, these materials must also endure the mechanical stresses caused by temperature fluctuations and dynamic maritime conditions. Additionally, the cost of these materials, their availability, and their environmental impact play a pivotal role in decision-making, making the material selection process a complex and multifaceted task (Patel, 2023).

This review aims to provide a comprehensive overview of the materials used in marine heat exchangers, with a focus on their thermal conductivity, corrosion resistance, and overall mechanical performance. By synthesising existing literature, we will examine the trade-offs among various materials — metals, alloys, and newer composite materials — in terms of both thermal and corrosion performance. Understanding the intricate relationship between material properties and operational conditions is essential for optimising heat exchanger design, particularly in the maritime sector, where performance and reliability are crucial. This review also highlights emerging trends, including the use of phase change materials (PCMs) and composite systems, which have the potential to revolutionise heat exchanger efficiency and sustainability in the future (Pakalka et al., 2020; Lin et al., 2020).

A heat exchanger allows the transfer of thermal energy between two different fluids while ensuring that the fluids do not mix each other. Heat exchangers are widely employed in many industrial and residential settings, including refrigeration, air conditioning and power production. The two fluids can exist in either liquid or gaseous states, and they move through distinct channels or plates within the heat exchanger. Heat transfer in the plate heat exchanger takes place by conduction, convection, or radiation, which is determined by the heat exchanger design and operating conditions. A plate-type heat exchanger is mainly used for allowing thermal transfer between two fluids, ensuring that the fluids remain separate and are not in contact with each other. The plate heat exchanger achieves this by utilising a sequence of metallic plates with channels for the passage of the two fluids. The plates are positioned in an arrangement that promotes the circulation of fluids through alternating channels and can provide effective heat exchange between them. Plate heat exchangers are commonly used in diverse industrial sectors, such as HVAC systems, refrigeration, chemical processing, and power generation.

The selection of the materials for plate-type heat exchangers depends upon the application and the nature of the fluids involved. However, typical materials utilised for the plates involve stainless steel, titanium, and other alloys. The selection of these materials relies on their corrosion resistance and capacity to endure high temperatures and pressures. The gaskets utilised for sealing the plates together are basically composed of rubber compounds such as nitrile rubber, EPDM, or Viton. These materials are chosen for their chemical resistance and capacity to maintain an intact seal subjected to elevated pressure and temperature. The choice of plate-type heat exchangers in industries and aboard ships involves various considerations. These heat exchangers are distinguished by their compact design, taking up minimal space, a critical factor in ship applications where space is at a premium. They efficiently transfer heat between fluids, boosting overall energy efficiency. With a lightweight construction, they contribute to reducing the overall weight, a vital consideration in marine applications. The materials used exhibit corrosion resistance, particularly important in marine environments exposed to seawater. The adaptability of these heat exchangers allows them to effortlessly meet the requirements of diverse systems, showcasing versatility for a wide range of ship applications. The multitude of benefits associated with plate-type heat exchangers underscores their widespread adoption and effectiveness in optimising the efficiency of marine systems (Zhang et al., 2019).

The material selection process for plate heat exchangers (PHEs) is intricate and involves several factors, including the intended usage, operational conditions, and the nature of the fluids being processed. Different industries may demand unique materials for their Plate Heat Exchangers (PHEs) based on these considerations. In the food and beverage industry, Plate Heat Exchangers (PHEs) commonly utilise stainless steel or other materials meeting food-grade standards. This is crucial to ensure that the processed fluids remain untainted. In the chemical processing sector, Plate Heat Exchangers (PHEs) may opt for materials resistant to corrosion and chemically inert, such as titanium or nickel alloys. Operating conditions significantly impact material choices for PHEs. High-temperature applications often call for materials with robust thermal conductivity and resilience to thermal stress. When dealing with highly corrosive fluids, materials exhibiting high corrosion resistance become paramount. Beyond the plates, even the gaskets and other components of PHEs can be composed of various materials, selected based on specific applications.

Overall, the meticulous selection of materials for PHEs is pivotal in ensuring their effectiveness, durability, and safety across diverse industrial applications. Plate heat exchangers, known as PHEs, are commonly found on ships, serving various roles like cooling motors, hydraulic systems, and lubricating oil. The materials chosen for PHEs on ships depend on factors such as the specific use, the environment in which they operate, and the rules governing material use in maritime settings. Materials for PHEs on ships are typically chosen for their ability to withstand harsh weather conditions, corrosion, and the demanding marine environment. Titanium, nickel alloys, and stainless steel are often used to make

PHEs on ships because they can handle the high temperatures and pressures in maritime applications and have good resistance to corrosion. Beyond the plates, materials resistant to seawater and other corrosive fluids might also be used for gaskets and other parts of PHEs on ships. Using the right materials is crucial to ensure the performance, reliability, and safety of PHEs in maritime conditions (Pandya et al., 2020).

For enhancing the heat transmission in plate heat exchangers on ships, a common approach involves using devices called vortex generators. These generators are inserted into the flow of a fluid to create a controlled swirling or vortical flow. This swirling motion helps improve how the fluid transfers heat by promoting mixing and disrupting the formation of boundary layers. This, in turn, increases the fluid's overall heat transfer efficiency. The study mentioned explored the impact of different types of vortex generators on heat transfer enhancement in plate-fin heat exchangers. The generator types included simple rectangular winglet (SRW), rectangular trapezius vortex generator (RTW), angular rectangular vortex generator (ARW), Wishbone vortex generators (WW), intended vortex generator (IVG), and wavy vortex generator (WVG). By using vortex generators in plate heat exchangers on ships, there's potential to enhance thermal performance and increase energy efficiency, both crucial factors in optimising the operation of marine systems. Vortex generators are like handy tools that can passively control the flow of fluids in heat exchangers and other systems. They are designed to create controlled swirls or vortices in the fluid, which can do things like reduce flow separation, improve heat transfer, and make the whole system work better. In heat exchangers, these vortex generators are often used to mix the fluid more efficiently and prevent the development of boundary layers. This can lead to better heat transfer between the fluid and the surfaces of the heat exchanger. Vortex generators come in different shapes, like basic rectangular winglets, trapezoidal vortex generators, angular vortex generators, wishbone vortex generators, and wavy vortex generators. These devices are strategically placed along the flow route to enhance heat transfer and create the desired swirling flow patterns. All in all, vortex generators are a useful tool for improving how fluids move and transfer heat in various technical applications, including heat exchangers, aeroplane wings and turbomachinery.

In engineering, there are two main ways to control fluid flow and improve heat transfer: passive methods and active methods. Passive methods use devices or changes that do not need extra power. They rely on the natural traits of the system and fluid movement. Examples include adding fins or dimples to surfaces, using vortex generators, and placing turbulators strategically. Since passive methods do not need more energy or control systems, they are often simpler and cheaper. Active methods, on the other hand, use external power to modify flow and boost heat transfer. This might involve using pumps, fans, or actuators to actively control heat transfer and flow patterns. While active methods offer precise control, they can be more complex and costly due to the need for extra equipment. Both passive and active methods are vital for improving heat transfer and system efficiency in heat exchangers and fluid systems. The best choice depends on the specific needs of the application (Samadifar & Toghraie, 2018).

2.0 ENTHALPY

The pillow-plate heat exchanger is specifically developed for applications involving latent heat thermal energy storage (LHTES). It has a distinctive layout with several flow channels that are filled with a phase change material (PCM) known as sodium acetate trihydrate. This novel design presents potential benefits for diverse energy storage applications, such as solar water energy storage systems, heat pump water heaters, and waste heat recovery systems that incorporate numerous working fluids (Lin et al., 2020).

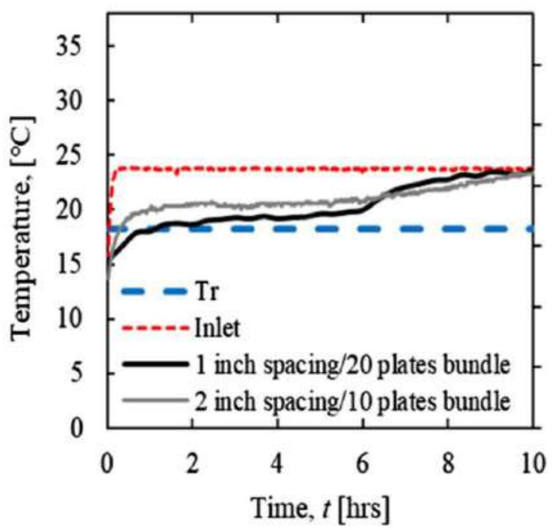
The main objective of the experiment was to thoroughly assess the thermal efficiency of this innovative LHTES system. The researchers performed charging and discharging experiments at different flow rates, while keeping the charging water temperature at 75 °C and the discharging temperature at 25 °C. The inquiry involved a comprehensive examination of temperature distributions in both the phase change material (PCM) and the heat transfer fluid (HTF). In addition, the study aimed to evaluate the operational capacity, energy efficiency, efficacy, and overall heat transfer coefficient and heat transfer area (UA) value of the LHTES system (Cerezo et al., 2022).

An important discovery was the impact of flow rates of the heat transfer fluid on the process of melting and solidification of the phase transition material. Increased flow rates were shown to be associated with accelerated phase transition processes, suggesting a dynamic correlation between fluid flow and the efficiency of energy storage and retrieval. The study also found that the system's operational efficiency improved as the flow rates increased, demonstrating the versatility and responsiveness of the innovative LHTES design to varying operational situations (Wang et al., 2022).

The results of the discharging tests demonstrated significant achievements in energy storage and retrieval. The energy that was regained varied from about 4.3 to 6.3 megajoules, depending on the flow rates that ranged from 100 to 500 litres per hour. Furthermore, the mean power remained rather consistent, oscillating between 2 kW and 5 kW for most of the test period. These findings highlight the system's capacity to continually generate a substantial amount of recovered energy while maintaining a relatively steady power output (Cerezo et al., 2022; Lin et al., 2020).

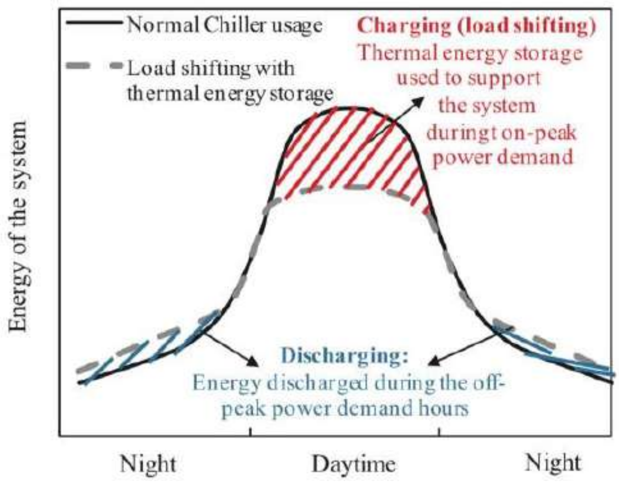
The study also examined the UA value, which quantifies the system's overall heat transmission efficiency. Throughout the range of experiments, the UA value fluctuated between approximately 25 W/k and 70 W/k at flow rates ranging from 100 L/h to 500 L/h. Notably, the UA value showed a small rise while the system was being charged, offering vital information on the thermal characteristics of the system during various operational stages (Wang et al., 2022).

Ultimately, the experimental evaluations revealed that the unique LHTES system, equipped with a pillow plate-type heat exchanger and phase change material, exhibited remarkable thermal efficiency. The results highlight the capacity of the PCM heat storage system to be an effective solution for various practical applications, including renewable energy solutions and waste heat recovery projects. The adaptability and dependability of this novel heat exchanger design are demonstrated by its dynamic reaction to changing flow rates and its consistent energy recovery during discharging experiments. These findings underscore its potential for use in a wide range of energy storage applications, encouraging further investigation and adoption (Lin et al., 2020; Cerezo et al., 2022).



(Saeed et al., 2019)

Fig. 1. Energy Conversion and Management



(Saeed et al., 2019)

Fig. 2. A typical load profile of an industrial thermal system

3.0 MATERIAL USED IN THE INDUSTRY

3.1 Phase Change Material

A phase-change material (PCM) is a substance capable of releasing and absorbing significant amounts of energy during a phase transition, which can be utilised for heating and cooling purposes. The transition typically occurs between the two fundamental states of matter: solid and liquid (Pakalka et al., 2020).

In general, heat exchangers and thermal energy storage systems based on PCMs show potential for enhancing energy efficiency, advancing heat transfer technologies, and supporting sustainable industrial processes. Ongoing research focuses on maximising their performance and addressing related challenges (Saeed et al., 2019).

PCMs can enhance the energy efficiency of heat exchangers. They offer improved energy efficiency and reliability in industrial processes, contributing to sustainable production and heat energy recovery. By utilising PCMs in heat exchangers, there is a notable increase in energy storage density compared to traditional materials, allowing for more effective heat storage and recovery processes (Lin et al., 2020).

The study investigates different methods aimed at improving the thermal conductivity of PCMs. Methods include utilising heat exchangers equipped with various types of fins and incorporating carbon powder, driving advancements in heat transfer technologies (Patel, 2023).

PCMs are also economically viable. Rapid advancement in the development of heat exchangers using PCMs is crucial for attaining economic viability in various industrial and non-industrial applications. This has the potential to result in reduced costs associated with the upkeep of infrastructure and its equipment. PCM receives financial assistance for research and innovation. This research is a component of the SusPIRE project and is supported by funding from the European Union's Horizon 2020 research and innovation program. The project's financial support highlights its importance in contributing to sustainable energy solutions (Saeed et al., 2019).

However, the usage of this material may present some challenges and limitations. PCMs encounter difficulties in heat storage systems due to their low thermal conductivity. This necessitates the creation of complex heat exchanger geometries and may lead to extended melting and solidification processes, especially when there is a need for high energy recovery and storage rates. Efficient heat exchange with PCMs may require intricate heat exchanger designs, resulting in higher production expenses and significant challenges in system design and implementation (Samadifar & Toghraie, 2018). Furthermore, several PCMs display undesirable attributes such as inadequate thermal stability, significant flammability, excessive supercooling, corrosive properties, and fluctuations in volume and pressure during phase transition procedures, which provide practical difficulties in their use. To overcome these restrictions, continuous research and development endeavours are necessary to improve the practicality and suitability of PCMs in different industrial and technical environments. The main areas of concentration should be enhancing thermal conductivity, material properties, and overall system efficiency (Zhang et al., 2019).

3.2 Composite of Phase Change Material and Metallic Foams

A composite material that combines Phase Change Material (PCM) with metallic foams for heat exchangers is commonly known as a PCM-enhanced or PCM-infiltrated metallic foam. This combination capitalises on the distinct characteristics of both phase change materials (PCMs) and metallic foams to construct a highly efficient and successful heat exchange system (Ferfera & Madani, 2020; Kiepfer et al., 2024).

The combination of phase change material (PCM) with metallic foams provides several advantages and possible uses in thermal management and heat exchange systems. The intentional use of metallic foams with PCM represents a significant improvement in heat transmission properties. By combining the excellent thermal conductivity of metallic foams with the latent heat absorption and release capabilities of PCM, this composite material permits a highly effective and rapid exchange of heat. This improvement is especially beneficial in a wide range of applications, including electrical devices and industrial systems, guaranteeing optimised temperature control and performance (Deisenroth et al., 2018). This material also exhibits superior thermal energy storage capabilities. The combination of PCM's high latent heat capacity and the porous structure of metallic foams results in a composite material that provides an efficient solution for storing thermal energy. This composite allows the material to effectively absorb, retain, and release thermal energy as needed. The composite material possesses diverse attributes that might be beneficial for sectors that need meticulous temperature regulation and energy storage applications, especially in renewable energy systems (Yin et al., 2018).

The composite is designed to excel in situations that need quick absorption and dissipation of heat and demonstrates improved thermal conductivity. The linked architecture of metallic foams, along with the phase shift capabilities of PCM, guarantees effective heat conduction across the material. This enhancement greatly improves the overall effectiveness of thermal management systems, making it a desirable option for businesses where thermal performance is crucial (Pelanconi et al., 2021). The use of metallic foams in the composite material not only improves thermal characteristics but also allows for the development of compact heat exchangers and thermal management systems. This ability is particularly advantageous in cases where there is limited space, providing a solution for industries that demand efficient heat transfer in small spaces, such as automotive applications and miniature electronic devices (Zettler et al., 2005). The versatility of the composite material renders it appropriate for a diverse array of sectors, such as electronic thermal management, prioritising precision and efficiency, and in building energy systems to provide optimal temperature control. Moreover, its ability to store and maintain thermal energy makes it a useful resource in renewable energy applications, enabling the sustainable control of heat in many technical and industrial environments (Jamzad et al., 2019).

Although the combination of PCM and metallic foams has several advantages, it is important to acknowledge the potential downsides or restrictions associated with this composite material. Incorporating metallic foams into the composite material may potentially decrease the total storage capacity of the PCM. The decrease in volume may be attributed to the presence of the metallic foam structure in the composite, which impacts the overall area available for storing PCM. Thoroughly assessing the balance between improved heat transport abilities and the possible decrease in storage capacity is essential to ensure that the composite material satisfies the specific needs of its intended use

(Kiepfer et al., 2024). The manufacturing processes used to produce composite materials that include PCMs and metallic foams are frequently complex and sophisticated. These procedures may involve meticulous infiltration or encapsulation methods to guarantee a uniform dispersion of PCM within the metallic foam structure. The intricacy of these manufacturing processes might result in higher production costs and necessitate a sophisticated manufacturing environment, thus introducing additional complexity to the entire fabrication process (Samadifar & Toghraie, 2018). Ensuring compatibility between PCMs and metallic foams is a crucial factor in the advancement of composite materials. Compatibility difficulties might occur due to disparities in material qualities or possible chemical reactions. Thorough testing and analysis are necessary to ensure the enduring stability and effective functioning of the composite material when exposed to different temperature conditions and thermal cycling (Zhang et al., 2019).

The primary factors of utmost importance are the mechanical robustness and structural soundness of the composite material, especially when subjected to several phase change cycles. Phase transitions may cause expansion and contraction in materials, which can generate stress and potentially result in structural problems over time. Engineers must meticulously engineer the composite material to endure these pressures and guarantee its longevity across a lengthy operating lifespan (Pelanconi et al., 2021). The inclusion of metallic foams in the composite material may result in increased expenses, especially when high-performance or specialised metallic foams are necessary. To assess the feasibility of using the composite material in certain applications, it is necessary to evaluate the improved thermal characteristics in relation to the economic factors through a cost-benefit analysis. The complete cost evaluation considers several factors, like material selection, production complexity, and overall system performance (Jamzad et al., 2019). The maintenance issues for the composite material revolve around guaranteeing its long-term durability, particularly in applications characterised by cyclic thermal loads. Repeated thermal cycling has the potential to cause material fatigue or deterioration over time. To limit the danger of performance deterioration and prolong the lifespan of the composite material, it is crucial to implement proactive maintenance measures, such as conducting regular inspections and considering the replacement of components when necessary (Ferfera & Madani, 2020).

3.3 Polymer Composite

Polymer composites are formed by the amalgamation of two or more constituent elements, resulting in the creation of a new material that possesses improved characteristics. Within the realm of heat exchangers, polymer composites can be formed by integrating fillers or reinforcements into the polymer matrix to enhance certain attributes like thermal conductivity, mechanical strength, or resistance to corrosion. The fillers or reinforcements used in heat exchanger applications might consist of materials like carbon fibres, silicon carbide whiskers, nano-clay platelets, and other additions that improve the overall performance of the polymer composite (Deisenroth et al., 2018; Pelanconi et al., 2021).

There are various benefits to utilising polymer as the material for a heat exchanger. One of its properties is that it is a substance with chemical resistance. Polymers frequently possess the ability to endure exposure to different substances at moderate temperatures and pressures. The chemical resistance of the heat exchanger is advantageous in situations where it encounters corrosive chemicals (Zhang et al., 2019). Polymer is also characterised by its cost-effectiveness. Polymers are often more economical than conventional metal products. The cost-benefit of polymer-based heat exchangers might make them an appealing choice, particularly in industries where financial concerns are of utmost importance (Yin et al., 2018). Therefore, this material also possesses intricate geometrical structures. The inherent malleability of polymers enables the fabrication of intricate shapes that might pose difficulties or be unfeasible using conventional production techniques. This feature is very advantageous in optimising the design of the heat exchanger to improve efficiency and performance. It is crucial to acknowledge that polymers do provide these benefits; yet there are also obstacles linked to their use, such as the aforementioned reduced heat conductivity. Nevertheless, continuous research and advancements strive to tackle these obstacles and enhance the versatility of polymer-based heat exchangers across diverse sectors (Samadifar & Toghraie, 2018; Deisenroth et al., 2018).

A fundamental limitation of this material is its diminished thermal conductivity. Polymers have a poorer thermal conductivity compared to metals, which might limit their efficacy in some heat transfer applications. Ongoing research is focused on addressing this limitation by the incorporation of conductive additives and the development of advanced composite materials. Nevertheless, metal still exhibits superior thermal conductivity. Polymer exhibits very low structural strength compared to other materials. The somewhat inferior mechanical integrity of polymers, in comparison to metals, may be a potential issue in situations involving significant stress or strain (Ferfera & Madani, 2020). Engineers frequently must meticulously evaluate material choice and reinforcing techniques to guarantee the structural soundness of the heat exchanger. Certain polymers may demonstrate inadequate thermal stability, limiting their use for applications that demand resistance to extreme temperatures (Patel, 2023). Scientists are now engaged in the development of heat-resistant polymers and composite materials to broaden their range of uses in such situations. The potential for some polymers to catch fire at elevated temperatures is a crucial factor to take into account, particularly in situations where ensuring fire safety is important. To reduce this danger, one might use fire-retardant chemicals or choose intrinsically flame-resistant polymers (Pelanconi et al., 2021). The susceptibility of polymers to fluid and moisture absorption can impact their performance and longevity. This is particularly important in applications where exposure to liquids or humid conditions is prevalent. Sealants and coatings are often employed to mitigate absorption issues. The durability of polymers can differ depending on environmental factors and the characteristics of the material. It is essential to comprehend the precise demands of the application, taking into account variables such as exposure to UV radiation, chemicals, and mechanical strain, in order to accurately anticipate and guarantee the durability of heat exchangers made from polymers (Ferfera & Madani, 2020).

3.4 Ceramic Lattice Structure

Silicon Carbide (SiC) is a ceramic compound consisting of silicon and carbon. This material is characterised by its hardness, brittleness, high melting point, and exceptional thermal and electrical conductivity. Silicon carbide (SiC) is extensively utilised in diverse industrial applications owing to its exceptional blend of characteristics, such as elevated temperature endurance, high thermal conductivity, and resistance to oxidation. SiC is regarded as a highly promising material for high-temperature heat exchangers because of its thermal qualities and its compatibility with additive manufacturing (AM) production (Pelanconi et al., 2021; Zhu et al., 2021).

The advantage of ceramics is their capability to enhance heat transfer performance. The intricate lattice structures in ceramics offer a high specific surface area, facilitating enhanced heat transfer. This increased surface area allows for efficient heat exchange between the fluids, contributing to improved overall performance. Another advantage of this material is its high temperature resistance. Ceramic materials, such as Silicon Carbide (SiC) and other advanced ceramics, have excellent thermal stability and can endure high temperatures often seen in heat exchangers used in high-temperature applications. The presence of this resistance is essential in order to sustain the structural integrity and functionality for prolonged durations (Kiepfer et al., 2024). Then, the utilisation of additive manufacturing (AM) methods, such as 3D printing, allows for the creation of complex lattice structures with personalised patterns. Engineers can customise the heat exchanger's shape to meet individual needs, enhancing its efficiency for certain uses (Nekahi et al., 2019). Lastly, ceramic lattice arrangements facilitate the production of heat exchangers that are both small in size and light in weight. This is especially beneficial in areas where weight concerns are critical, such as aerospace or automotive applications. The decreased weight might also facilitate the process of installation and transportation. The combination of these advantages makes ceramic lattice structures a highly attractive choice for high-temperature heat exchangers, particularly in situations that need effective heat transfer in difficult working circumstances. Nevertheless, it is crucial to acknowledge that some obstacles, such as fragility and the expense associated with advanced ceramics, must be tackled. Consequently, continuous investigation is expected to concentrate on enhancing these materials and production techniques to facilitate wider acceptance in the industrial sector (Zhang et al., 2019).

Ceramic materials have inherent brittleness and are prone to fracture. Structural breakdowns can occur as a result of thermal cycling and mechanical loads, which are frequently encountered in high-temperature applications. Due to its brittleness, it is important to carefully analyse the constraints of the material and adopt design features or operating techniques to reduce the risk of failure (Patel, 2023). The fabrication of ceramic lattice structures utilising additive manufacturing (AM) methods may undoubtedly be intricate and time-consuming. Other than that, higher manufacturing expenses are typically incurred due to the necessity of specialised equipment and knowledge. The intricacy of the lattice structures may also cause issues in terms of quality control throughout the production process. Both ceramic materials and AM processes often incur greater costs compared to traditional production methods. This element can provide a substantial constraint, particularly in businesses where cost is a critical consideration. Nevertheless, progress in manufacturing techniques and the benefits of producing on a larger scale might potentially mitigate these cost-related worries in due course (Pelanconi et al., 2021).

Last but not least, although lattice structures provide certain design freedom, they may not be suited for heat exchanger applications that need extremely detailed fluid flow patterns or complex geometries. This constraint may limit the scope of applications in which ceramic lattice structures are feasible (Al-Ghani et al., 2022).

Ceramics can be regarded as a viable substitute for metals in heat exchangers. Heat exchangers made of ceramic offer superior performance in situations involving high or ultra-high temperatures or while handling corrosive fluids, due to their exceptional resistance to corrosion and temperature (Al-Ghani et al., 2022; Nekahi et al., 2019).

The examination of heat exchanger technologies and coatings emphasises the ongoing pursuit of innovative methods to enhance the longevity and effectiveness of heat transfer. Heat exchangers tend to be made using advanced materials such as titanium composites, nickel alloys, stainless steels, corrosion-resistant alloys, and ceramic composites. These materials provide exceptional thermal characteristics, including a high thermal conductivity that enhances the rate of heat transfer between fluids. Additionally, it provides an extra layer of protection against challenging working conditions, resulting in enhanced heat transfer rates and overall efficiency (Patel, 2023).

3.5 Aluminium Nitride

Aluminium nitride (AlN) is recognised for its excellent heat conductivity, proving it highly beneficial for a wide range of applications. Incorporating AlN into composites can enhance thermal conductivity as a result of its natural properties. The thermal conductivity of AlN is 58.21 W/m/K, which increases the overall thermal conductivity of the materials. Furthermore, the thermal conductivity of AlN can be affected by its microstructure, which encompasses factors such as particle size and porosity (Yin et al., 2018).

Aluminium nitride (AlN) is a type of advanced ceramic that has notable thermal conductivity. An advanced thermal conductivity leads to a more indeed dissipation of temperature. The increased heat conductivity of AlN reduces the threat of unwanted thermal gradients, hence dropping the liability of material fracture. In addition to its high thermal conductivity, AlN possesses special characteristics like a good hardness of 17.7 GPa, a high melting point of 2700 K, and an outstanding elastic modulus of 310 GPa (Nekahi et al., 2019).

The heat exchanger constructed of AlN exhibited a significant improvement in heat transfer, with a 59% enhancement compared to the one made of Al2O3. The significant improvement can be attributed to the superior heat conductivity of AlN in comparison (Fattahi et al., 2020).

The utilisation of AlN-based materials in heat exchangers is in line with the wider attempts to enhance both the efficiency and the reliability of thermal management systems in diverse sectors, such as automotive, aerospace, electronics, and industrial operations (Yin et al., 2018).

3.6 Natural Graphite

Due to its remarkable characteristics, natural graphite is highly regarded as an appropriate material for heat exchanger applications. Natural graphite is a versatile and advantageous choice due to its corrosion resistance, impressive thermal conductivity ranging from 300 to 600 $W \cdot m^{-1} \cdot K^{-1}$ in the in-plane direction (in contrast to aluminum's 200 $W \cdot m^{-1} \cdot K^{-1}$), low density of 2.1 $g \cdot cm^{-3}$ (compared to aluminum's 2.7 $g \cdot cm^{-3}$), negligible coefficient of thermal expansion, and cost-effectiveness (Samadifar & Toghraie, 2018; Jamzad et al., 2019).

Manufacturers in the field of graphite heat exchangers, such as SGL Carbon and Group Carbone Lorraine, have utilised artificial synthetic resin impregnated graphite to produce top-quality units. These units are sold under the DIABON® and GRAPHILOR® trademarks, respectively, and are known for their exceptional performance. The production procedure entails exposing artificial graphite blocks to exceedingly high temperatures, reaching up to 3000 °C, in order to induce the formation of crystalline structures. Subsequently, these blocks are carefully and precisely processed to get the intended configuration for application in the heat exchanger sector. Although artificial graphite possesses corrosion-resistant properties, the extensive utilisation of thermal goods derived from this material has been hindered by the substantial expenses involved in its manufacturing and machining processes (Pelanconi et al., 2021).

Recent progress in fabrication processes has opened up opportunities for improved efficiency and cost-effectiveness, namely with the use of the roll-embossing process. This novel method enables the efficient and cost-effective manufacturing of graphite sheets with diverse designs. The benefits of utilising natural graphite, in conjunction with these innovative manufacturing methods, are specifically emphasised in the advancement of chevron-type plate heat exchangers, as demonstrated in this research (Kiepfer et al., 2024; Al-Ghani et al., 2022).

The study showcases a proof-of-concept demonstration of a novel production technique for chevron-type plate heat exchangers, employing the flat embossing process. This innovative method shows potential for enhancing the efficiency, corrosion resistance, and cost-effectiveness of graphite-based heat exchangers, making them ideal for various industrial applications. In order to evaluate the effectiveness of the suggested graphite plate heat exchanger, a specially built water-water experimental setup is created, following the guidelines of ANSI/AHRI Standard 400 (Zhang et al., 2019).

A comparative examination was conducted between a standard stainless-steel chevron HEX and a HEX with similar plate dimensions and quantities. The results obtained were found to be intriguing. The proposed graphite plate heat exchanger demonstrates equivalent thermal performance to the commercially available unit, confirming its effectiveness in heat transfer applications. Nevertheless, it also exhibits a 26% increase in pressure loss, which can be attributed to its narrower channel design. This attribute, although impacting the pressure dynamics, provides opportunities for additional investigation and enhancement in future designs (Ferfera & Madani, 2020; Patel, 2023).

The distinctive blend of characteristics found in natural graphite, along with progress in manufacturing methods, provides a promising prospect for creating heat exchangers that not only match the thermal efficiency of traditional metal alloys but also provide benefits in terms of resistance to corrosion and cost-effectiveness. This research acts as a first stage in uncovering the full capabilities of natural graphite in the field of heat exchanger applications. With the ongoing search for inventive solutions that effectively combine performance, durability, and cost-effectiveness, the potential for the broad acceptance of heat exchangers made from graphite is becoming more and more encouraging (Pelanconi et al., 2021; Al-Ghani et al., 2022).

3.7 Polymer Graphite Hollow Fibre

The thermal performance of polymer hollow fibre heat exchangers is as follows: Although the polymers used have low thermal conductivity (less than 0.4 W/mK), hollow fibres with small inner diameters (less than 100 µm) can produce very high heat transfer coefficients. These coefficients range from 500 to a maximum of 2100 W/m²K for liquid-liquid heat transfer (Kiepfer et al., 2024; Pelanconi et al., 2021). Given the absence of empirical data, the maximum operational pressure for this design is uncertain. This uncertainty arises from the design's utilisation of thin walls, which restricts it to the low-pressure range. An example of this would be PEEK (Polyether Ether Ketone), which is mechanically highly stable but comes at a high cost (Zhang et al., 2019). This design does not allow for the straightforward replacement or addition of individual components, such as what is achievable with the PHE, for the sake of cleaning or enlargement.

The available literature on polymer-based plate heat exchangers is scarce. However, one notable example is a cross-flow heat exchanger made of PEEK, which achieves impressive total heat transfer coefficients of up to 900 W/m²K. It is worth noting that this performance is achieved under a high maximum pressure of 10 bar. The comparison demonstrates the higher thermal performance of the heat exchangers created in this study when low wall strengths are employed. Additional research on polymer plate heat exchangers has been conducted; however, the majority of these studies primarily concentrate on air-to-air heat transfer, therefore preventing any meaningful comparisons (Saeed et al., 2019). As previously stated in the introduction, numerous studies have been conducted on the advancement of thermally conductive composites. However, none of these studies specifically focus on the development of a plate heat exchanger. Nevertheless, when comparing the thermal conductivities of the created materials with existing data from the literature, it becomes evident that they exhibit relatively low thermal conductivity. For instance, the thermal conductivity of the PP-graphite composites is 12.4 W/mK, whereas those with a graphite mass fraction of 80% have a thermal conductivity of 15.5 W/mK (Yin et al., 2018).

The fundamental cause can be attributed to the production process. The aforementioned authors produce their composites by the process of injection moulding. The technique employed in this case is extrusion, resulting in the alignment of particles inside the same plane. As an illustration, the PPS-graphite composites, which were likewise manufactured using extrusion, have a through-plane thermal conductivity of 1.65 W/mK when the graphite mass fraction is 50%. The thermal conductivity of the PPS-graphite composites discussed in this study is 2.01 W/mK, with a graphite mass percentage of 65%. The alignment of fillers (in the case of anisotropic fillers) is crucial in determining the creation of thermal conduction pathways. Nevertheless, this is frequently linked with more intricate manufacturing techniques (Samadifar & Toghraie, 2018).

Alfa Laval AB currently offers DIABON types as graphite heat exchangers in the market. The latter appears to be a viable and economically efficient method, as the material yields comparable heat flows to metallic heat exchangers, as demonstrated in the study. Unfortunately, the reference does not provide any information regarding thermal conductivities or heat transfer coefficients, making it impossible to make a direct comparison. The DIABON F100 heat exchanger from Alfa Laval closely resembles the heat exchanger produced here in terms of its ability to withstand high working temperatures and resist chemicals (Pelanconi et al., 2021).

3.8 Diamond composites with higher thermal conductivity

Diamond, an extraordinary and distinctive substance, has outstanding thermal conductivity, rendering it a fascinating contender for applications such as plate-type heat exchangers. Diamond exhibits a considerably greater thermal conductivity compared to conventional heat exchanger materials such as stainless steel or aluminium. This aspect is a result of the robust covalent bonding and crystal structure of diamond, which enables it to effectively transfer heat across its lattice (Dai et al., 2020; Samadifar & Toghraie, 2018).

The core objective of plate-type heat exchangers is to enhance the thermal exchange between two fluid streams. Utilising diamond as the material for the plates could result in significant benefits. Diamond's exceptional thermal conductivity facilitates fast and effective heat transfer between the fluids circulating within the exchanger. The improved heat transfer efficiency could lead to enhanced overall performance and heightened energy efficiency of the heat exchange process (Pelanconi et al., 2021). Moreover, the remarkable hardness and durability of diamond might enhance the longevity and dependability of the heat exchanger. The equipment's durability and resistance to wear and corrosion can increase its lifespan, resulting in reduced maintenance needs and operating downtime (Ferfera & Madani, 2020).

Nevertheless, there are certain obstacles that need to be taken into account while considering the use of diamond in plate-type heat exchangers. The expense of producing diamond components, along with the difficulties linked to machining and shaping this resilient material, can pose economic barriers. Furthermore, it is crucial to thoroughly assess the industrial scalability and practicality of integrating diamond into heat exchanger systems. The cost of producing diamond components is substantial due to the complexity of manufacturing and shaping diamond (Zhang et al., 2019). In summary, although the theoretical benefits of using diamond in plate-type heat exchangers are fascinating, it is crucial to carefully evaluate practical factors such as expenses, manufacturing difficulties, and scalability. Ongoing research and development in the field of materials science are focused on finding new and creative ways to improve the efficiency of heat exchangers. Diamond, with its unique features, has the potential to be used in specialised thermal management systems (Kiepfer et al., 2024).

3.9 Phase change material (porous material)

The PCM can be integrated into a metal framework, which may take the shape of a matrix composed of carbon brushes, basic metallic elements, or a foam produced from a naturally porous substance like graphite or copper foams. Velraj et al. conducted experiments on latent heat storage units utilising metallic rings. The metal rings have demonstrated high efficiency, with the thermal conductivity of the ring-paraffin assembly (2 W m^{-1} K^{-1}) being ten times greater than the thermal conductivity of the paraffin alone (0.2 W m^{-1} K^{-1}) (Zettler et al., 2005). Furthermore, carbon is utilised in the fabrication of such formations. The structures are protected against deterioration caused by gravity and the weight of the installation due to the low density and high thermal conductivity of the material. The major issue to be considered for improving global transfer in systems involving PCM is the effective thermal conductivity of the assembly structure.

Carbon brushes are positioned in vertical tubes within an exchanger, whereas carbon-fibre chips are distributed throughout the main body of a tank. Regarding carbon brushes, the tubes are put into the framework and firmly pressed into the carbon to provide effective thermal contact. The effective conductivity of carbon-fibre chips in the bulk is higher compared to the organised carbon-fibre chips. As an illustration, when considering a metallic structure with a volume of 1%, the ratio between the effective thermal conductivity of the structure and the thermal conductivity of the PCM (Phase Change Material) is 3.3 for carbon brushes and 3.7 for carbon-fibre chips (Saeed et al., 2019).

Nevertheless, the utilisation of bulk carbon-fibre chips results in the formation of thermal resistance in proximity to the exchange surface, due to inadequate contact with the tubes. Consequently, this diminishes the overall efficiency of heat transfer. The global heat transfer coefficient is 340 W m^{-2} K^{-1} for carbon brushes compared to 150 W m^{-2} K^{-1} for carbon-fibre chips (Pelanconi et al., 2021).

In the conduction of a preliminary investigation to examine the enhancement of heat transmission in $NaNO_3$ by including a metal foam. The observations revealed a twofold augmentation in the rate of heat transmission when porous materials were included instead of pure $NaNO_3$ (Zhang et al., 2019). This technique involves combining a foam or metal structure with a porosity of approximately 90% with a phase change material (PCM) through compression or impregnation. The approach has already been utilised by researchers, mostly with copper (Yin et al., 2018).

Zhang et al. (2019) conducted a study on the utilisation of paraffin and graphite foams to create composite PCM. This study observed that increasing the thickness of the graphite ligament and reducing the size of the holes can lead to increased thermal diffusivity. The combination of a wide pore size and slender graphite ligament led to an enhancement in latent heat storage (Kiepfer et al., 2024). Xiao et al. examined the effect of using metal foam to enhance the equivalent thermal conductivity in quasistationary situations. It was deduced that the thermal conductivity equivalent depends on the porosity and thermal conductivity of the various materials, rather than the size of the pores (Patel, 2023).

Additional research has mostly concentrated on enhancing the phase change behaviour in metallic foams and has identified a correlation between pore size and the enhancement of phase change. For instance, when the porosity is constant and the size of the pores is small, a higher pore density is observed. This leads to an increased potential for enhancing heat transfer by creating a larger surface area for exchange. While there is a plethora of theoretical, analytical, and numerical investigations on metal foams, only a restricted number of practical experiments have produced tangible and encouraging outcomes. Frequently, experimental investigations are conducted on minuscule quantities of foam, which may not necessarily replicate the conditions of an actual storage tank (Samadifar & Toghraie, 2018).

A study was conducted where they submerged a tube bundle-type exchanger in an aluminium foam that was infused with PCM. It was compared to the exchanger with a single tube bundle. It was discovered that the introduction of foam into the tube bundle during solidification resulted in a 20% improvement in performance. Additional tests were conducted to facilitate fusion. The performance was subsequently enhanced by 100%, notwithstanding the foam's disruption of convection motions between the upper and lower sections of the exchanger (Ferfera & Madani, 2020). Furthermore, the researchers constructed a computational model and determined a thermal conductivity of 5.1 W m^{-2} K^{-1} for the process of solidification and 1.8 W m^{-2} K^{-1} for the process of fusion (Zettler et al., 2005).

3.10 Coating Fibre

Coating fibres emerges as a strategic and versatile method to enhance the thermal conductivity of composites, driven by several key considerations. The process of coating fibres enhances heat transfer by improving the interface contact between the fibres and the matrix within the composite material. This heightened interface interaction facilitates more efficient thermal conduction, ultimately leading to an elevation in the overall thermal conductivity of the composite. Additionally, the coating of fibres provides a valuable tool for controlling and manipulating the thermal properties of the composite. Through precise adjustments to the composition and thickness of the coating layer, it becomes possible to tailor the thermal conductivity to meet specific performance requirements (Pelanconi et al., 2021; Zhu et al., 2021). Furthermore, the coating layer plays a critical role in reducing the interface thermal resistance between fibres and the matrix. This reduction proves significant in determining the composite's overall thermal conductivity, contributing substantially to the enhancement of heat transfer properties. Lastly, the flexibility inherent in the process of coating fibres allows for the incorporation of high-thermal-conductivity materials into the composite structure. This flexibility provides a means to improve thermal performance without necessitating significant alterations to the base matrix material (Patel, 2023; Samadifar & Toghraie, 2018).

In conclusion, the strategic use of coated fibres not only optimises heat transfer properties but also offers a versatile approach to tailoring the performance of composite materials for specific applications. The exploration of heat conductivity in fibre-reinforced composites, whether coated or uncoated, unfolds a perplexing and intricate design. The introduction of a coating layer amplifies this complexity, yielding a pronounced impact on thermal conductivity. The interplay between coating thickness and thermal conductivity becomes a pivotal factor in shaping the overall thermal characteristics. Delving into deeper layers reveals distinct and elusive patterns. In composites lacking coatings, a specific equilibrium is dictated by the thermal conductivity ratio between the fibre and the medium. Conversely, the realm of coated fibres introduces an additional perspective, where the thermal conductivity of the coating layer takes a crucial role in determining the normalised effective thermal conductivity (Zhang et al., 2019).

The scrutiny of heat transfer performance introduces further intricacies. Coated fibre-reinforced composites grapple with challenges arising from heat resistance at the interface and surface imperfections, casting a veil of uncertainty when compared to their uncoated counterparts. The arrangement of fibres significantly influences the sensitivity of the normalised effective thermal conductivity, adding to the conundrum. The impact of the coating layer varies depending on the distribution of fibres within the composites, exhibiting negligible effects on those with fibres randomly distributed in coordinate planes while exerting considerable influence on those with fibres dispersed randomly in space. This state of confusion underscores the imperative to analyse and comprehend the thermal complexities of fibre-reinforced composites with a sophisticated understanding, customised to the unique features and configurations of the fibres (Ferfera & Madani, 2020).

Fibres display exceptional thermal conductivity, stemming from a combination of key factors. Firstly, the material composition plays a pivotal role, with fibres like carbon and specific metals recognised for their high thermal conductivity, attributed to the inherent atomic and molecular structure of these materials. Secondly, the crystal structure of fibres, exemplified by the ordered arrangement in carbon fibres, facilitates efficient heat conduction along the fibre axis, enhancing overall thermal conductivity (Yin et al., 2018). The aspect ratio, representing the ratio of fibre length to diameter, is crucial, as longer fibres with higher aspect ratios act as effective conduits for heat conduction, positively influencing the thermal conductivity of composite materials (Patel, 2023). Additionally, fibres can undergo doping or modification to further enhance their thermal conductivity. An example is the integration of high-thermal-conductivity fibres like carbon fibres into phase change materials, resulting in a substantial increase in the composite material's overall thermal conductivity (Samadifar & Toghraie, 2018).

In combination, these factors contribute to the heightened thermal conductivity of specific fibres, making them invaluable for applications requiring efficient heat conduction, particularly in fields such as thermal energy storage and the development of energy-saving materials for buildings. The thermal conductivity of fibre-reinforced composites is intricately linked to the thickness of the coating layer, presenting several notable considerations. Firstly, the coating layer functions as a barrier to heat transfer between fibres and the matrix, leading to an overall reduction in the composite's thermal conductivity. This reduction becomes more pronounced with an increase in the thickness of the coating layer, emphasising the significant impact of this barrier effect (Zhu et al., 2021). Moreover, the effect of coating layer thickness on thermal conductivity is not uniform across different fibre arrangements. In composites with fibres randomly distributed in coordinate planes, the coating layer thickness exhibits minimal influence on the normalised effective thermal conductivity. However, in composites with fibres randomly distributed in space, the thickness significantly affects thermal conductivity, introducing a nuanced sensitivity to the spatial arrangement of fibres (Kiepfer et al., 2024).

A crucial aspect is the controllable nature of the coating layer thickness, serving as a process parameter during composite material preparation. This controllability provides a valuable avenue for optimising thermal conductivity. By strategically adjusting the thickness of the coating layer, one can fine-tune the material's overall thermal properties, showcasing the potential for tailored optimisation in thermal performance (Zhu et al., 2021).

4.0 SUMMARY OF MATERIALS USED IN THE INDUSTRY

Table 1. Summary of Materials used in industry for Marine Heat Exchangers

Material	Key Properties	Applications in Marine Heat Exchangers	Challenges/Limitations	References
Phase Change Materials (PCMs)	High latent heat capacity, energy storage during phase transition	Used for energy storage in thermal systems, enhances heat storage capacity	Low thermal conductivity, complex heat exchanger design required	(Pakalka et al., 2020)
Composite of PCM and Metallic Foams	Combines the high latent heat of PCM with the excellent thermal	Improves heat transfer and energy storage in heat exchangers	Manufacturing complexity, reduced storage capacity due to foam	(Ferfera & Madani, 2020)

	conductivity of metallic foams			
Polymer Composites	Chemical resistance, cost-effective, malleable for intricate designs	Cost-effective heat exchangers in industries with moderate temperatures	Low thermal conductivity, poor mechanical strength, and limited high-temperature use	(Deisenroth et al., 2018)
Ceramic Lattice Structures	High temperature resistance, excellent thermal stability	Ideal for high-temperature applications, can withstand extreme conditions	Brittle, susceptible to fracture, and high production costs	(Pelanconi et al., 2021)
Aluminium Nitride (AlN)	Exceptional thermal conductivity, high melting point, and hardness	Used in high-performance heat exchangers for efficient heat transfer	High production cost, limited to specific applications	(Yin et al., 2018 & Fattahi et al., 2020)
Natural Graphite	Excellent thermal conductivity, corrosion resistance, and low density	Used in graphite-based heat exchangers, particularly in corrosive environments	High production cost, limited scalability, and manufacturing challenges	(Jamzad et al., 2019)
Polymer Graphite Hollow Fibre	High heat transfer coefficients, flexible material design	Used in low-pressure, liquid-liquid heat exchangers	Low thermal conductivity of polymers, difficulty in scaling	(Kiepfer et al., 2024)
Diamond Composites	Outstanding thermal conductivity, high hardness, and excellent durability	Specialised thermal management systems in high-performance applications	Expensive, difficult to manufacture, and scalability issues	(Dai et al., 2020)

5.0 CONCLUSION

Upon thorough analysis of materials suitable for heat exchangers on boardships, the data overwhelmingly support the selection of aluminium nitrate as the premier option. Its remarkable thermal conductivity ensures optimal heat transfer efficiency, crucial for the demanding conditions at sea.

Furthermore, aluminium nitrate exhibits exceptional corrosion resistance, safeguarding the longevity of the heat exchanger amidst the corrosive marine environment. This characteristic reduces maintenance requirements, contributing to cost-effectiveness and prolonged operational lifespan.

The lightweight nature of aluminium nitrate adds another layer of advantage, enhancing the overall structural integrity of the heat exchanger without imposing unnecessary burdens on the ship's weight capacity.

In conclusion, the comprehensive attributes of aluminium nitrate position it as the ideal material for heat exchangers on board ships, promising heightened efficiency, durability, and operational resilience in maritime applications.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Challenges to Blockchain Adoption in Global Shipping: Insights from a Systematic Literature Review

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Abstract – Blockchain technology could transform global shipping. Replacing antiquated paper-based processes with a secure, immutable digital record of shipments would unlock efficiency gains, save costs, and reduce fraud. Yet blockchain has not been widely adopted. This study employs the PRISMA framework to systematically review the literature on the challenges to blockchain adoption in the global shipping industry. A total of 184 published documents from the Scopus database were identified, of which 54 journal articles met the study's eligibility criteria. By identifying and synthesising key barriers, the review provides valuable and comprehensive insights into the complexity of integrating blockchain technology into global shipping. The findings highlight practical challenges, such as substantial initial investment costs, and regulatory challenges, including uncertainty around dispute resolution, antitrust concerns, and data privacy and security, as pivotal to sustainable innovation and business model transformation through the adoption of blockchain technology in the sector.

Keywords: Blockchain, Shipping, Sustainable Innovation

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1.0 INTRODUCTION

Remarkably, the business of global shipping in the twenty-first century continues to rely heavily on the antiquated practice of presenting original (paper) shipping documents for cargo release, payment, and transfer of ownership of goods (Wilson, 2010). Shipping lines issue a physical (paper) bill of lading in a set of three originals to the consignor. One original bill of lading must be sent to the consignee and presented at the discharge port to claim delivery of the cargo. A second original of the bill of lading, together with the international contract of sale documents, will be sent to the consignee or their bank (where payment is secured by letter of credit). Blockchain technology is widely acknowledged as having the potential to transform this business model and eliminate the delays, costs and fraud associated with these paper systems.

The integration of blockchain technology in global shipping business models would provide a secure, immutable digital record of transactions between consignors and consignees in a shipping contract by storing the smart contract and delivering the bill of lading via a digital ledger (Takahashi, 2016). The blockchain is a permanent digital record (or ledger) that creates and stores transactions that are time-stamped and grouped in blocks linked to each other, as you would find in a chain. Each transaction entered into the blockchain database is authenticated by the consensus of every computer across the network, collaborating in this verification process (Manners-Bell & Lyon, 2019). A blockchain can store a comprehensive shipping contract in the form of a block of smart contracts that includes the terms of the contract of carriage, receipt of shipment, transfer of title and a bill of lading issued under charter-party (Bashir, 2018).

The potential advantages of integrating blockchain technology in the shipping industry are numerous, particularly regarding consignment tracking, accountability, transactional integrity and the form and period in which bills of lading are delivered to the appropriate consignees (Iansiti & Lakhani, 2017; Tricoli, 2018). While blockchain technology is not a cure-all for the logistical and regulatory problems in the shipping industry, it can serve as a practical solution to some problems, such as immutability and transactional integrity, cost reduction, consignment visibility, and the registration and real-time finalisation of bills of lading on decentralised ledger systems (Manners-Bell & Lyon, 2019).

Despite these advantages, blockchain technology has failed to secure widespread adoption in the global shipping industry. In 2022, the blockchain-enabled global trade digitisation platform, TradeLens, was discontinued, only four years after it was launched by a joint venture of container shipping giant AP Moller Maersk and IBM (Maersk, 2022). The platform was created in 2018 to establish a digitised trade system built on open standards and designed for use by shipping industries across the globe (TradeLens, 2022). TradeLens facilitated a paperless supply chain, enabling the secure and seamless exchange of information about shipment events in real time. The blockchain-based platform enabled end-users to securely submit, validate and approve digital documents across organisational boundaries, ultimately helping to reduce the time and cost for customs clearance and cargo movement (Manners-Bell & Lyon, 2019). The rationale for the termination of TradeLens was the lack of achievement of “full global collaboration”, which is a necessity for the goal of the project (Maersk, 2022). This is the most recent failure of a large-scale blockchain initiative in the sector and underscores the importance of investigating the barriers to adoption.

This study employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) framework to systematically review the literature on the challenges to blockchain adoption in the global shipping industry (Page et al., 2021). By identifying and synthesising key barriers, and grouping them thematically as practical and regulatory challenges, the study provides a valuable and comprehensive contribution to the discourse on sustainable innovation and business model transformation through the adoption of blockchain technology in the sector.

2.0 LITERATURE REVIEW

The study performed a systematic literature review, adopting the PRIMSA framework (Page et al., 2021). A systematic PRISMA review is a robust method to (a) retrieve relevant evidence on the study’s research problem, and (b), through appraisal and synthesis of the results, to inform practice and policy and identify areas for future research (Munn et al., 2018; Zhang & Gu, 2022). The systematic review process followed a standard procedure of literature search, quality assessment, data extraction, and synthesis (Mengist et al., 2020; Saif et al., 2022). The research team was composed of three academics with law backgrounds and based in South Africa.

2.1 Literature Review

The search was conducted on Scopus on 19 February 2024 by the first researcher. Scopus (Burnham, 2006; Zhu & Liu, 2020) was selected for its combination of comprehensive, rigorous coverage of scholarly literature and advanced search and filtering functionality (Bakkalbasi et al., 2006; Joshi, 2016; Martín-Martín et al., 2018). The search for keywords was applied to the title and abstract field using the following search query: TITLE-ABS-KEY (blockchain AND shipping OR maritime AND challenges OR solutions OR implementation). The search was unrestricted in date range because, although blockchain is a relatively new innovation, the study sought comparative insights to traditional business models. The search yielded 184 results.

2.2 Quality Assessment

A systematic screening process was applied as outlined in the PRISMA flow diagram (Figure 1). Using the filters on Scopus excluded 4 records not in English and 30 records not in peer-reviewed journal articles. The title, abstract, keywords, authors' names and affiliations, journal name, and year of publication of the remaining identified records were exported to an MS Excel spreadsheet (Annexure A). The first researcher then carried out a manual screening of the titles, abstracts, keywords, and full texts, applying the eligibility criteria for inclusion. No automation tools, machine learning classifiers, or generative AI devices were used to eliminate records. The third researcher audited the results.

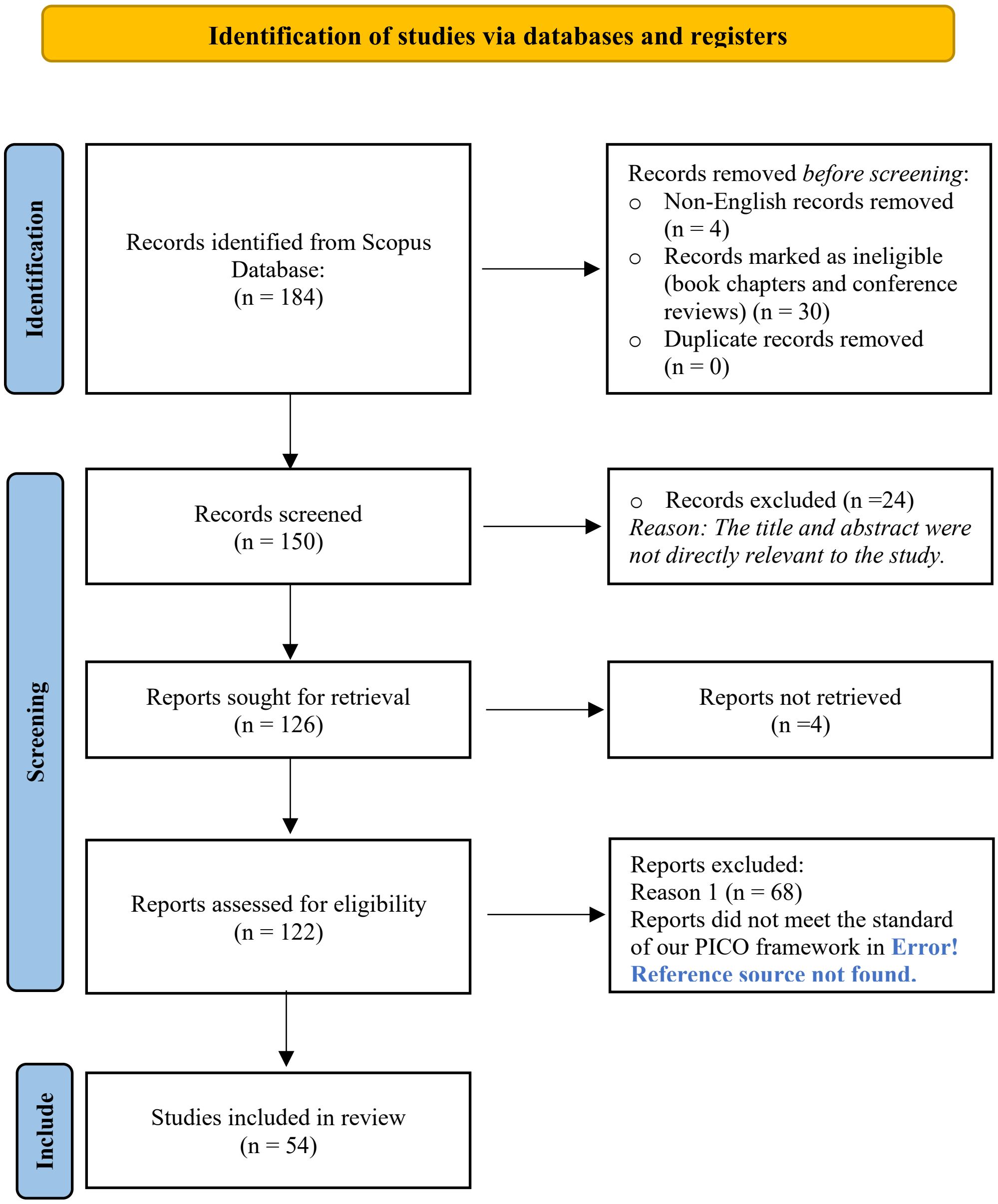

Figure 1: Flow Chart of Studies

2.3 Eligibility Criteria

The first and second research defined the eligibility criteria used to screen results according to the modified PICO (Problem-Intervention-Comparison-Outcome) model shown in **Error! Reference source not found.**. The PICO model is useful to develop research questions and define eligibility criteria for systematic searches (Frandsen et al., 2020). It was adopted in the present study in view of the highly diverse nature of the literature from various regions, industry sub-sectors and legal jurisdictions. As the study aimed to present a holistic, global or industry-wide review of challenges in blockchain implementation, publications were screened for high relevance according to whether they met all four criteria in the PICO model:

(P) Population & Problem: The study population was the global shipping industry. Publications were included if they contained a global or industry-wide discussion of practical or regulatory challenges in blockchain implementation. Studies that only focused on a specific region, enterprise or individual case study were excluded.

(I) Interventions: Publications presenting a qualitative analysis of an extant or terminated blockchain application in global shipping were included. Qualitative studies examine and interpret events and experiences within their broader legal and socio-economic context (MacEachen et al., 2016; Seale et al., 2004) and were selected as most appropriate to address the research objective of assessing the underlying reality of attempts to implement blockchain. Quantitative studies were excluded from the review.

(C) Comparison: the publication compared blockchain solutions to traditional models against one or more of the following indicators: cost, documentation, transactions or port operations, and

(O) Outcome: the publication findings discussed and analysed challenges.

Table 1: Modification of the PICO Framework

Modified PICO Framework

	Guidelines	Application
P	Patient/Population/ Problem	(Problem) Challenges to the implementation of Blockchain technology in the Shipping Industry, E.g. Cost, Regulations and Security
I	Intervention/Indicator	(Intervention) Highlighting both extant and terminated Blockchain frameworks that have replaced traditional models. E.g. Insurwave switching from Blockchain to SaaS and Maersk & IBM terminating Tradelens.
C	Comparison/Control	(Comparison) Comparing the efficiency in cost, documentation, transactions and port operations between Maritime stakeholders using Blockchain technology and maintaining traditional methods.
O	Outcome	(Outcome) Conclusions and findings that identify practical and regulatory challenges to the implementation of Blockchain technology in the Shipping Industry.

3.0 SUMMARY OF RESULTS AND ANALYSIS OF KEY FINDINGS

The analysis and synthesis of results first reviewed the implementation of blockchain technology in the maritime industry and then considered practical and regulatory challenges identified in the literature as barriers to adoption and technological innovation.

3.1 Implementation of Blockchain Technology in the Maritime Industry

Before its dissolution in 2022, TradeLens was the leading blockchain platform in the container shipping industry. The TradeLens blockchain platform provided three distinct features which were the platform, marketplace, and ecosystem (Lorenz-Meyer & Santos, 2023). The platform was the underlying blockchain feature that allowed stakeholders and third parties alike to share information. The platform also provided user interface programming to allow its users to build their own applications on the platform (Philipp et al., 2019). The marketplace function provided real-time connectivity across the supply chain, linking cargo owners, freight forwarders and regulators such as customs and border management agencies (TradeLens, 2020). The TradeLens 'ecosystem' allowed for easy and reliable data sharing, encryption, and validation (Jovanovic et al., 2022). Cargo details and shipping milestones, as well as other key trade documents, were protected from both internal and external mutation and alterations (Jensen et al., 2019). The platform was the most successful blockchain project in global shipping to date. As of 2022, TradeLens had processed over 20 million documents, over 2 billion events and more than 42 million shipments (Lorenz-Meyer & Santos, 2023). The platform had attracted some of the biggest ocean carriers and major terminal operators such as Hapag-Lloyd, the biggest German shipping company, ONE, Japan's biggest shipping company and HSBC, one of the world's largest banks and financial service providers (Lorenz-Meyer & Santos, 2023). However, the platform failed to achieve "full global collaboration", which was cited as the main reason for its discontinuation (Maersk, 2022).

While TradeLens remains the most prominent blockchain-based solution in the global shipping industry, there have been other initiatives. Shin and colleagues (2023) identified 20 blockchain-based products introduced in the maritime industry between 2017 and 2021. These initiatives are itemised in Figure 3 below (Shin et al., 2023). Each represents an innovative solution to pervasive problems in the shipping industry.

For example, T-Mining, a Belgian company, built a blockchain platform to efficiently catalogue the process of shipping containers by assigning digital tokens to each container as an alternative to the traditional method of pin codes (Loohuis, 2020). In addition, the company created ID wallets, which serve as a Self-Sovereign-Identity (SSI) tool to provide a secure medium for its members to connect and transact on the platform (Loohuis, 2020). In the United States, ShipChain, a US start-up, developed an Ethereum-based maritime logistics system (DHL Trend Research, 2018). ShipChain's platform monitored the movements of all types of shipping products, allowing for the execution of smart contracts and trading, through the company's cryptocurrency called Ship Token (Cuccuru, 2017; DHL Trend Research, 2018). However, the company was shut down in 2020 due to licensing issues with their cryptocurrency (Kingston, 2020).

The publications reviewed identified a broad range of application potential in the maritime industry, including ship registration systems, smart contracts to manage financial flows within the industry, crew certification systems for training and qualifications, bunker tracking systems to monitor fuel consumption, marine insurance, international contracts of sale, documentation flow (principally, transfer of the bill of lading) and container and cargo tracking in real-time (Munim et al., 2021). The studies also identify key reasons for the hesitation to adopt blockchain technology, as well as practical, legal, and regulatory challenges of blockchain technology in the industry.

Table 2: Blockchain Application Cases (Shin et al.)

Company types	Lead company	Name of project	Main partners	Participating members	Year	Role and aim
Shipping liner	MOL		NYK Kawasaki, and NTT Data	14 members	2017	Trade data sharing platform to streamline procedure and reduce costs
	Hyundai Merchant Marine		Oracle, Samsung SDS, IBM Korea, Busan Port authority	38 members	2017	Blockchain consortium for shipment booking and cargo delivery
	APL		Kuehne+Nagel, InBev, Accenture,		2018	Solution to eliminate shipping documents and save logistics costs
	Pacific International Lines		PSA International and IBM Singapore		2018	Blockchain-based electronic bill of lading to cut the traditional paper trail and streamline the process
	Maersk	TradeLens	IBM	300 members	2018	Open and standardised platform for interaction through real-time access to shipping data and shipping document, including IoT and sensor data
	Ocean Alliance carriers	GSBN (Cargo Release)	Bank of China, DBS Bank, HSBC		2019	Blockchain-based open platform to connect stakeholders and allow them to digitise and organise dangerous goods documentation
	China Merchants Energy Shipping	Britc	China Merchants group		2021	Reliable platform for a shipping service platform, a documentation and contract system, as well as an information-sharing centre in dry bulker and tanker industry
Port	Authorities at the Port of Antwerp		T-mining, PortXL programme		2017	Platform to optimise efficiency in the container handling logistics chain by eliminating physical paperwork
	ABU Dhabi Ports unit Maqta Gateway	Sisal	Maritime SC		2018	Blockchain system providing seamless and secure link between stakeholders across the trade community with encrypted documentation
	Port of Rotterdam Authority		Samsung logistics and ABN Amro		2018	Open, independent and global platform for paperless integration of physical, administrative and financial streams within international chain
Software companies	Marine Transport International		Solas VGM		2017	Programme leveraging the legal requirements
	ShipNext		300 cubits		2018	Selling digital token for secured and reliable transactions in cryptocurrencies
	300 Cubits		Westports, LPR		2018	Deposit system using BCT and TEU token to address the problem of cargo 'no-shows' and 'rollovers'
	EY and Guardtime	INSURWAVE		4 members	2018	Digital platform for marine hull insurance
	CARGOSMART		Oracle		2018	Solution for supply chain parties to auto-fill repeated and verified information
	CargoX				2018	Blockchain-based electronic bill of lading
	Wave BL		Hapag-Lloyd, Zim, MSC		2020	Blockchain-based electronic bill of lading
	BunkerChain	TrustTrade	Singapore's Infocomm Media Development Authority		2021	Real time visibility and control of the physical bunkering process with full audit trail
Insurance	LLOYD'S Register Foundation	MBL consortium	Blockchain Labs for Open Collaboration (BLOC)	8 members	2018	Tracking the risks and challenges associated with the declaration and handling of dangerous goods
Bank	BNP Paribas and HSBC Singapore				2018	Digitised letter of credit transaction and digitalisation of trade finance

3.2 Practical Challenges

The hesitancy to adopt blockchain-based solutions contrasts with the maritime industry's generally positive approach to adopting technological innovation (Zhang & Gu, 2022). Some authors note greater caution in relation to risk-taking and organisational change among senior decision-makers (Gausdal et al., 2018). Yet, it is puzzling that blockchain is not being adopted more widely, particularly in relation to digital document transfer. Global shipping is information-intensive, involving the exchange of large amounts of data between multi-sector stakeholders from shipping organisations, traders, logistics service providers, and regulators (Gausdal et al., 2018). Disruptions to data exchange can result in liabilities of up to $5 million per day, while poor information management can account for as much as a 20% deficit in operating budgets (Den Norske Veritas DNV, 2016). This warrants closer examination of the reasons behind the shipping industry's reluctance to adopt technological solutions to address these problems.

Gausdal and colleagues (2018) identified barriers to digital innovation. First, the authors highlight the high cost of adoption and the uncertain return on investment (Cygler & Sroka, 2016). Initial investment costs, including energy, equipment and training, are very high. This can be discouraging, especially when there is no guarantee of its effectiveness (Li et al., 2024).

Secondly, as shipping is a global business, the adoption of digital solutions is problematic due to limited and slow internet services in some parts of the world (Gausdal et al., 2018). Blockchain solutions and real-time freight analysis and tracking rely heavily on the Internet (Zhou et al., 2020).

Thirdly, diffusion and adoption rates within the sector are highly variable and are particularly low among small and medium-sized enterprises (SMEs). This may be explained by the constrained capacity of SMEs to invest in IT systems and software. Thus, a few large companies and tech start-ups have been early adopters of the technology. Without sector-wide adoption, blockchain solutions cannot reach their full potential.

3.3 Legal and Regulatory Challenges

The maritime industry is heavily regulated across all sectors by both international and national agencies. This complex regulatory framework complicates efforts to achieve standardisation. Furthermore, legal frameworks are currently inadequate to regulate new technologies (Deffeyes, 2001; Schellekens, 2022) with significant amendments required (European Commission, 2020). The resultant regulatory uncertainty impacts confidence in dispute resolution measures, anti-trust laws, and data privacy and security (Thanaraj, 2021), which emerged from the review as key legal concerns (Peronja et al., 2020). Moreover, the challenge of complying with multiple (and sometimes incompatible) regulations and standards has the potential to stifle blockchain innovation and implementation (Lacey et al., 2015). Clear regulations and standards for blockchain technology must be developed to address adoption hesitancy (Gausdal et al., 2018).

3.3.1 Dispute Resolution

Dispute resolution in the maritime industry is already complicated. The global nature of the industry presents jurisdictional challenges, differences in substantive rights, and procedural rules. These difficulties are exacerbated in relation to the adoption of novel technologies (Greenstein, 2022; Todd, 2019).

Technological advancements in the exchange and execution of electronically generated documents have revealed several gaps and inadequacies in legal regulation (Mahmoud, 2023). Many jurisdictions have begun amending or developing procedural rules to accommodate the use of electronic documents and smart contracts (Swales & Mahmoud, 2023). However, despite progress, rules relating to electronic evidence still require harmonisation (Mahmoud & Bellengere, 2020).

3.3.2 Antitrust Regulations and Blockchain Transparency

Antitrust regulations are designed to prevent monopoly, price manipulation and other anti-competitive practices. In the maritime industry, sharing of sensitive information such as pricing, production levels, and market allocation is highly restricted (e.g. the United States of America Sherman Antitrust Act, 1980). Consequently, the transparency feature of blockchain poses a significant challenge to its adoption. Blockchain is designed in a way that all information shared on the platform is visible to all permitted users in the case of a private blockchain and to anyone in the case of a public blockchain. To this end, the exchange of information on a blockchain platform potentially violates extant legal requirements (Jović et al., 2019).

3.3.3 Regulation of Data Privacy and Security

While security is one of the primary benefits of blockchain platforms, they are not foolproof. Blockchains, particularly public platforms, are susceptible to security breaches such as denial of service (DoS), eclipse attacks, man in the middle (MitM), and signatures can be deciphered with technological advancements such as quantum computing, compromising blockchain data, since it is immutable (Abdallah et al., 2023). Most of the attacks on blockchain platforms targeted cryptocurrencies due to vulnerabilities in application software, smart contracts, and protocols (Orcutt, 2019). Although improved security measures have been implemented in response to these incidents, the claims that blockchain is secure have been tarnished, leading to fears about the privacy and security of data in the event of a data breach (Abdallah et al., 2023). Most of the blockchain platforms used in the maritime industry are private, and this significantly reduces the chances of security breaches (Li et al., 2024). This is because the validation process is assigned to certain users, reducing, but not eliminating, the risk of a data breach (Munim et al., 2021). The laws and policies regulating the maritime industry at both the national and international levels need to be updated to include data security concerns on blockchain platforms and clarify data privacy rights and responsibilities in order to rebuild stakeholder confidence (Perkušić et al., 2020).

4.0 CONCLUSION

The review identified a large corpus of published literature addressing the benefits and potential of blockchain platforms in the global shipping industry, but much of the research was region-specific or narrowly focused on specific sub-sectors of the industry or individual case studies. This systematic literature review offers a holistic global review that identified 54 highly relevant academic studies that discuss blockchain's application and the practical and regulatory challenges to its implementation in global shipping practice.

Despite its potential to transform global shipping, the study found that unless there is sector-wide acceptance of blockchain, the technology does not present a viable alternative to traditional business models. This is especially relevant to secure document exchange solutions like TradeLens, where sector-wide adoption by all stakeholders is necessary for blockchain to reach its full potential (Papadakis & Kopanaki, 2022).

Secondly, the study found that the shipping industry remains hesitant to adopt blockchain for two primary reasons: switching costs and regulatory concerns. Switching to a blockchain solution involves substantial investment in technology infrastructure and training of staff (Lorenz-Meyer & Santos, 2023). The switching cost is amplified by first-mover disadvantages, as cost savings and efficiency gains are only fully realised when most stakeholders adopt the technology (Jensen et al., 2019). Thus, paradoxically, companies prefer to avoid the risks and costs associated with being early adopters of the technology. Regulatory uncertainty presents a further challenge, with a lack of clarity around the application of rules pertaining to electronic evidence in the resolution of disputes and concerns about how anti-trust laws apply to information shared on the blockchain. Moreover, shipping companies are cautious about divulging confidential information, proprietary knowledge, and intellectual property on blockchain platforms, as they are sceptical about the adequacy of security and privacy safeguards (Lorenz-Meyer & Santos, 2023).

In conclusion, this paper recommends that regulators at both the international and national levels work to address the regulatory lacuna and enhance capacity building across the sector to provide the basis for technological innovation and the adoption of new business models in the shipping sector.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Ammonia Reliability as Primary Refrigeration for Air Conditioning System

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Abstract

This paper explores the reliability and advantages of ammonia (R-717) as a primary refrigerant for air conditioning systems in comparison to hydrofluorocarbons (HFCs). With growing environmental concerns and stringent regulations targeting ozone-depleting substances and high global warming potential (GWP) refrigerants, ammonia emerges as a sustainable and efficient alternative. Ammonia offers zero ozone depletion potential (ODP) and near-zero GWP, coupled with superior thermodynamic properties that enhance energy efficiency and reduce operational costs. Despite its toxicity and flammability, advancements in safety protocols, system design, and operator training have significantly mitigated associated risks, enabling safe and dependable industrial and commercial applications. The study highlights ammonia's high latent heat of vaporisation, low boiling point, and favourable thermophysical characteristics that contribute to its outstanding coefficient of performance (COP) compared to HFCs. Furthermore, ammonia's environmental benefits are demonstrated through a substantial reduction in carbon emissions, with a Total Equivalent Warming Impact (TEWI) that is up to 68% lower than that of common HFC refrigerants. The paper also discusses the practical considerations for ammonia system safety, including risk assessment, leak detection, and emergency response measures aligned with international standards. While HFCs remain prevalent due to ease of handling and lower toxicity, their environmental impact and regulatory phase-down underscore the need for alternatives like ammonia. This comprehensive assessment supports ammonia's position as a reliable, eco-friendly, and economically viable refrigerant, aligning with global sustainability goals and future regulatory frameworks for air conditioning systems.

Keywords: ammonia, air conditioning, refrigerant reliability, energy efficiency, environmental sustainability

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1.0 INTRODUCTION

In the pursuit of sustainable and efficient refrigeration technologies, selecting the right refrigerant is crucial for optimising system performance, minimising environmental impact, and ensuring operational safety. Refrigeration is a process where heat is removed from a space or system by lowering and maintaining its temperature below the ambient temperature. Refrigeration is essential for advancing sustainable development because it supports a wide range of applications, including air conditioning, food storage, chemical manufacturing, and biomedical processes. Among the diverse refrigerants available today, ammonia refrigerant (R-717) and hydrofluorocarbons (HFCs) emerge as leading candidates, each offering unique benefits and presenting certain challenges. Although HFCs have gained traction due to their relatively low toxicity and user-friendly handling, ammonia continues to set the standard for reliability, energy efficiency, and environmental sustainability in both industrial and commercial refrigeration applications.

As regulations on chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and HFC refrigerants become increasingly strict, and with the complete phase-out of CFCs and HCFCs on the horizon, there is a strong focus on finding alternative refrigerants for existing refrigeration systems. These alternatives must not only possess thermodynamic properties like halocarbons but also be safe for both human health and the environment (Society of Heating & Engineers, 2002).

Ammonia stands out with its zero global warming potential (GWP) and zero ozone depletion potential (ODP), making it a far more environmentally responsible choice compared to HFCs, which often have GWPs ranging from several hundred to thousands. Additionally, ammonia's superior thermodynamic properties translate into outstanding energy efficiency, frequently surpassing that of HFC refrigerants, which leads to reduced operating costs and a smaller carbon footprint throughout the system's lifespan. (Pearson,2008).

Despite concerns related to ammonia toxicity and flammability, advancements in safety protocols, comprehensive operator training, and robust system engineering have rendered ammonia refrigeration systems exceptionally safe and reliable (Pearson, 2008). Conversely, HFC refrigerants, though generally safer in terms of toxicity, face drawbacks such as significant environmental impact (in the case of HFCs). Furthermore, ammonia's adaptability to large-scale industrial applications, including Heating, Ventilation, and Air Conditioning (HVAC) chillers, process cooling, and district cooling, further highlights its unparalleled reliability and durability.

This article presents a detailed comparison of ammonia and HFC, examining their respective strengths. It makes a compelling case for why ammonia remains the most dependable and advantageous refrigerant choice for air conditioning systems, supported by scientific evidence and extensive industry experience.

2.0 REFRIGERATION FOR AIR CONDITIONING SYSTEM

Refrigeration is a fundamental component in air conditioning systems, enabling the transfer of heat from indoor spaces to the external environment to maintain comfortable temperatures and humidity levels. Central to this process is the use of chemical substances that absorb and release heat as they circulate through the system's compressor, condenser, and evaporator. Two types of refrigerants used in air conditioning systems are ammonia (R-717) and HFC. Each has distinct characteristics that influence its application and environmental impact.

2.1 Ammonia

Ammonia is employed as an effective alternative to CFC-based refrigerants, which were banned in 1970 due to their adverse effects on the environment (Khudhur et al., 2022). Ammonia refrigerant (R-717) was among the earliest refrigerants utilised and continues to be commonly used in industrial refrigeration today (SensitronSrl, 2025). R717 has been introduced in refrigeration systems since the early 20th century. Ammonia (NH_3) is a chemical compound consisting of one nitrogen atom and 3 hydrogen atoms. Nitrogen is in Group 15 of the periodic table and has five valence electrons, enabling it to form covalent bonds with three hydrogen atoms. In this arrangement, NH_3 has no net charge, making it a neutral molecule without any positive or negative charges. In refrigeration systems, this neutral charge enables ammonia to circulate smoothly without causing disruption or reacting unexpectedly (Mike LaFollette, 2025).

Ammonia's high latent heat of vaporisation offers a key benefit over CFCs and HFCs by enhancing the coefficient of performance (COP) of refrigeration systems, leading to increased energy efficiency (Buhari et al., 2024a). Ammonia can absorb more heat during its phase change (from liquid to vapour) than most other refrigerants. This means the system requires a smaller mass of ammonia to achieve the same cooling effect, resulting in lower refrigerant charge and reduced stress on system components. NH_3's notably low boiling point of about -33.3°C reduces the number of compression stages required in the refrigeration cycle, boosting efficiency and leading to significant energy savings (Charge of NH3, n.d.). A properly designed ammonia refrigeration system achieves the same cooling capacity with seven to eight times less system circulation (Kuhlman, 2021).

One of ammonia's key advantages is its minimal environmental impact. Unlike synthetic refrigerants such as HFCs and HCFCs, ammonia is a naturally occurring gas that does not contribute to the greenhouse effect (Sharma, 2023). Ammonia is regarded as an environmentally friendly refrigerant with zero GWP and minimal ODP, making it a more sustainable option compared to HFCs, which pose greater environmental risks due to their higher GWP and flammability (Park et al., 2023). Potential cost savings come from lower spending on piping and installation. Ammonia's efficient properties allow the use of smaller diameter pipes. (Hayes, 2023). Table 1 presents the physicochemical properties of ammonia and compares them with those of other refrigerants. It is a comparison of ammonia, HCFCs, HFCs, and blended HFCs about GWP and ODP. It shows that ammonia has the lowest GWP and ODP.

Table 1: Physicochemical properties of ammonia and comparison with other refrigerants (Buhari et al., 2024b)

Refrigerant	Ammonia	Hydrochlorofluorocarbons (HCFCs)	Hydrofluorocarbons (HFCs)	Blend HFC
IUPAC Chemical Name	Ammonia	Chlorodifluoromethane	1,1,1,2-Tetrafluoroethane	1,1,1-Trifluoroethane, Pentafluoroethane, 1,1,1,2-Tetrafluoroethane
Chemical Formula	NH_3	$CHClF_2$	CF_3CH_2F	CF_3CH_2F, CF_3CH_3, CF_3CH_2F
ASHRAE Number	R-717	R-22	R-134a	R-404A
Physical State	Gas	Liquefied gas	Liquefied gas	Liquefied gas
Melting Point (°C)	-78	-160	-101	Not determined
Boiling Point (°C)	-33	-40.8	-26.06	-46.7
Critical Temperature (°C)	133	96.1	100.6	72.1
Water Solubility (g/l)	510 – 531	2.6	1.82	0.73
Latent Heat of Vaporisation at Boiling Point (kJ/kg)	1247.85	201.79	195.52	162.03
Flammable Limits (Lower / Upper)	16% / 25%	Not determined	Not determined	Not determined
GWP	>1	1820	1430	3260
ODP (100 Year)	0	0.055	0	0.20
Atmospheric Lifetime (years)	-	13.3	14.6	-

2.2 Hydrofluorocarbons (HFCs)

The adoption of HFCs has facilitated the swift elimination of ozone-depleting substances (ODS) such as halons, CFCs, and HCFCs, particularly in areas where alternative options were limited. HFCs have largely replaced the demand for ODS across various sectors, including refrigeration and air conditioning, insulating foams, propellants in metered dose inhalers, technical aerosols, specialised fire suppression systems, and other uses (Godwin & Ferenchiak, 2020a). HFCs have largely replaced the demand for ODS across various sectors, including refrigeration and air conditioning, insulating foams, propellants in metered dose inhalers, technical aerosols, specialised fire suppression systems, and other uses. As these technologies, especially refrigeration and air conditioning, continue to expand globally, the use and emissions of HFCs are projected to rise substantially (Godwin & Ferenchiak, 2020b).

HFCs are a class of refrigerants that have gained prominence in the refrigeration and air conditioning sectors due to their chemical composition, which includes carbon, fluorine, and hydrogen. Unlike their predecessors, CFCs and HCFCs, HFCs do not contain chlorine, which means they do not contribute to the depletion of the ozone layer. This characteristic has made HFCs a preferred choice in many applications, particularly in the European Union, where regulations have led to the banning of CFCs and HCFCs in various sectors since 2011 (Messineo, 2012). Besides their advantages in ozone layer protection, HFCs are not concerned about environment. They are potent greenhouse gases, which may lead to significant global warming. The refrigeration sector has been under pressure to transition from HFCs to more environmentally friendly alternatives due to their high GWP (Messineo, 2012). The energy consumption that is associated with refrigeration systems also plays a crucial role in greenhouse gas emissions, as the electricity is often generated by sources of fossil fuel, which further exacerbates climate change (Messineo, 2012).

HFCs are characterised by their high volatility and extremely low solubility in water. Once released into the environment, these substances primarily remain in the atmosphere. Regarding safety and health considerations, HFCs are widely utilised as refrigerants and fire suppression agents because they are generally non-flammable at room temperature and standard atmospheric pressure. Nevertheless, under certain conditions, HFCs can create flammable mixtures when combined with air. Compared to HCFCs, HFCs typically exhibit lower toxicity. Extensive toxicological assessments on commonly used HFCs have been carried out by the Program for Alternative Fluorocarbon Toxicity Testing (PAFTT) (Wen-Tien Tsai, 2005). It has long been understood that all organic chemicals have the potential to affect the environment. HFCs, which are also classified as volatile organic compounds (VOCs), exhibit particularly notable characteristics, most prominently their high volatility and hydrophobic nature compared to related substances like saturated chlorocarbons. As a result, the atmosphere is the primary reservoir where these compounds tend to accumulate following their release. It is widely acknowledged that HFCs are suitable substitutes for CFCs and HCFCs, as they share many comparable physical and thermochemical characteristics (Wen-Tien Tsai, 2005).

3.0 AMMONIA DEPENDABILITY IN THE AIR CONDITIONING INDUSTRY

Ammonia is increasingly recognised as a dependable refrigerant in the air conditioning industry due to its efficiency and low environmental impact. It is widely used in industrial refrigeration applications because of its properties of high energy efficiency, which results in lower operational costs for businesses. Ammonia has zero ODP and negligible GWP, which makes it an environmentally friendly choice compared to other synthetic refrigerants that can cause climate change and ozone layer depletion (Buhari et al., 2024c). Since it has zero ozone depletion and making it an attractive option for reducing greenhouse gas emissions in the air conditioning sector, this aligns with the global initiatives such as the Montreal Protocol, which aims to eliminate harmful refrigerants and promote alternatives that are less damaging to the environment. In addition, ammonia's low volumetric efficiency can limit its application in conventional vapour compression systems, although it is more suitable for sorption-based systems (Uddin & Saha, 2022). Moreover, the ongoing research regarding ammonia's physicochemical properties and its behaviour under various operating conditions is essential for improving its dependability as a refrigerant. Understanding the reactivity and safety characteristics of ammonia allows engineers and safety professionals to be aware of and improve risk assessment practices and regulations, ensuring that ammonia can be used safely in air conditioning systems and can reduce the risk to the operator (Buhari et al., 2024).

Ammonia is a highly efficient refrigerant, outperforming most HFCs and CFCs in terms of energy efficiency. It absorbs more heat per pound, allowing refrigeration systems using ammonia to operate with lower energy consumption. In contrast, systems relying on HFCs and CFCs typically need larger capacities to deliver the same cooling effect. This efficiency is largely due to ammonia’s low boiling point of -28°F, which enables it to vaporise easily and absorb substantial heat during phase changes, thereby enhancing its cooling capacity. This characteristic allows ammonia systems to achieve effective heat exchange with less refrigerant mass. Traditional refrigerants like R-134a, however, have higher boiling points and lower latent vaporisation heat, limiting their heat absorption efficiency (Messineo, 2012). Another critical thermophysical property of ammonia is its phase change behaviour. Ammonia exhibits superior heat transfer performance during phase transitions, particularly during the processes of evaporation and condensation. These phase changes, where ammonia shifts between its liquid and gaseous states, are fundamental to the operation of vapour-compression refrigeration cycles. The high latent heat and consistent thermodynamic characteristics of ammonia during these transitions enhance the efficiency and reliability of refrigeration systems, making it a highly effective working fluid in thermal management applications. Ammonia adheres to classical saturation thermodynamic relationships, wherein a direct correlation exists between pressure and temperature under conditions of vapour-liquid equilibrium. This well-defined and predictable behaviour is fundamental to the design and operation of refrigeration systems, as it enables precise determination of the thermodynamic conditions required for optimal system performance. For example, at atmospheric pressure, ammonia reaches equilibrium between its vapour and liquid phases at a specific temperature, a characteristic that is critical for ensuring consistent efficiency and control within refrigeration cycles. Furthermore, ammonia exhibits relatively low density under standard conditions, with both its gaseous and liquid phases being less dense than air and water, respectively. This characteristic facilitates improved fluid dynamics within refrigeration systems, enabling efficient circulation and distribution of the refrigerant, thereby enhancing overall system performance (Ammonia Data Book 2nd Edition, 2008).

In addition, ammonia's high solubility in water presents both advantages and challenges in refrigeration applications. While this property can be leveraged in specific system designs, it also necessitates careful control measures to mitigate potential corrosion, particularly in environments where moisture is present. From a sustainability perspective, ammonia's composition, consisting solely of nitrogen and hydrogen, both naturally abundant elements, further supports its viability as an environmentally responsible refrigerant in line with current trends toward greener refrigeration technologies (Ammonia Data Book 2nd Edition, 2008).

4.0 RESULT OF DISCUSSION

4.1 Efficiency and Performance of Ammonia

The actual Coefficient of Performance (COP_{actual}) serves as an indicator of a cooling system's efficiency. It is determined by the ratio of the refrigeration effect to the work input by the compressor. Mathematically, it can be expressed as:

$$COP_{actual} : \frac{q_k}{w_k} = \frac{h_1 - h_4}{h_2 - h_1}$$

The refrigeration effect is the amount of heat that the refrigerant absorbs (q_k) from the environment or product being cooled. It is calculated by finding the difference in enthalpy between the evaporator outlet and inlet, where h_1 is the enthalpy at the evaporator outlet, and h_4 is the enthalpy at the evaporator inlet, both expressed in kJ/kg.

Compressor work (w_k) refers to the amount of heat absorbed by the refrigerant per unit mass during the refrigeration process. It is determined by the difference in enthalpy between the compressor outlet and inlet, where, h_1 is the enthalpy at the compressor inlet, and h_2 is the enthalpy at the compressor outlet, both measured in kJ/kg.

This ratio effectively measures how efficiently the system utilises energy to transfer heat. In contrast, the ideal Coefficient of Performance (COP_{ideal}) reflects the theoretical upper limit of the refrigeration system's efficiency. It is calculated by dividing the evaporator temperature by the temperature difference between the condenser and evaporator, represented as:

$$COP_{ideal} = \frac{T_e}{T_c - T_e}$$

where *Te* denotes the evaporator inlet temperature and *Tc* represents the condenser inlet temperature.

The efficiency of the refrigeration machine is evaluated by comparing the actual COP to the ideal COP. It provides insight into how closely the system operates to its theoretical maximum efficiency. The formula used for this calculation is:

n = (COPactual/COPideal)×100%*n=COPactual/COPideal×100%* (Cholik et al., 2024)

The system efficiency over a 10-day period was calculated using Equation (Dharmavaram et al., 2023), and the results are presented in Fig. 1. Fig. 1 shows the efficiency values ranged from a minimum of 77% on Day 3 to a maximum of 91% on Day 5 align with the findings of (Wang et al., 2022) who conducted thermodynamic analyses of combined cooling and power systems and noted similar efficiency fluctuations based on varying operational parameters.

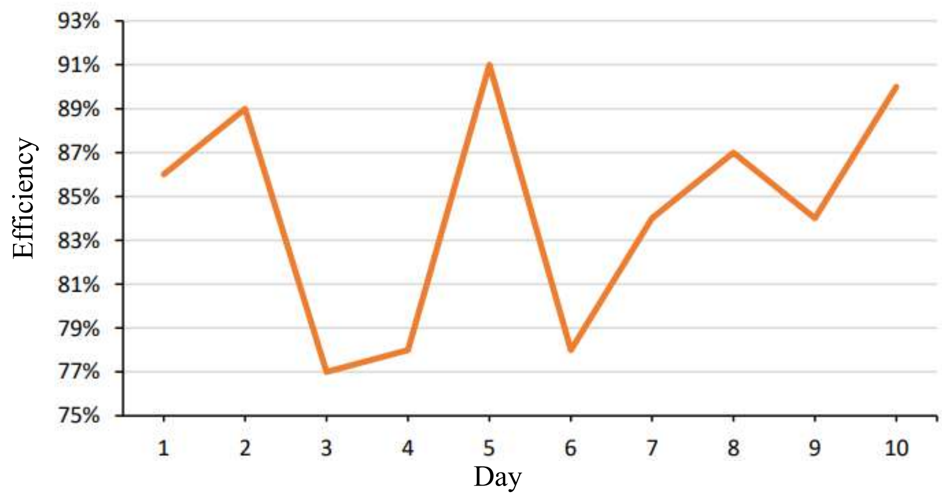

Fig. 1. Efficiency of the ammonia refrigeration system (Cholik et al., 2024)

4.2 Thermophysical Properties of Ammonia

Ammonia demonstrates distinctive thermophysical properties, namely thermal conductivity, specific heat, and viscosity, that are critical to its performance as a heat transfer fluid and its widespread use in industrial processes. These properties are strongly temperature and phase-dependent, which enhances ammonia's versatility in thermal systems. In both gaseous and liquid phases, ammonia exhibits relatively high thermal conductivity, significantly contributing to its superior heat transfer capabilities compared to many other substances. Furthermore, its high specific heat in both phases reinforces its effectiveness in absorbing and transporting thermal energy. Although the viscosity of ammonia, in either phase, is generally moderate relative to other fluids, it remains within a suitable range for efficient circulation in thermal systems. Fig. 2 shows the specific heat of ammonia liquid. The graph displays how the specific heat (in Btu/lb·°F) of a saturated liquid changes with temperature (in °F).

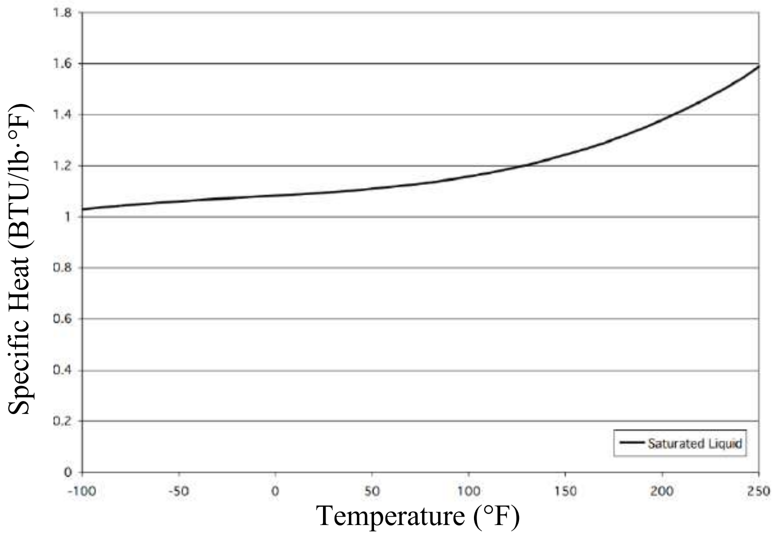

Fig. 2. Specific Heat of Ammonia Liquid (Ammonia Data Book 2nd Edition, 2008)

Ammonia in its gaseous state exhibits high thermal conductivity (k) compared to most other substances. This property makes ammonia highly effective for heat transfer applications. Fig. 2 shows the thermal conductivity values of ammonia in its liquid form and in its gas/vapour form.

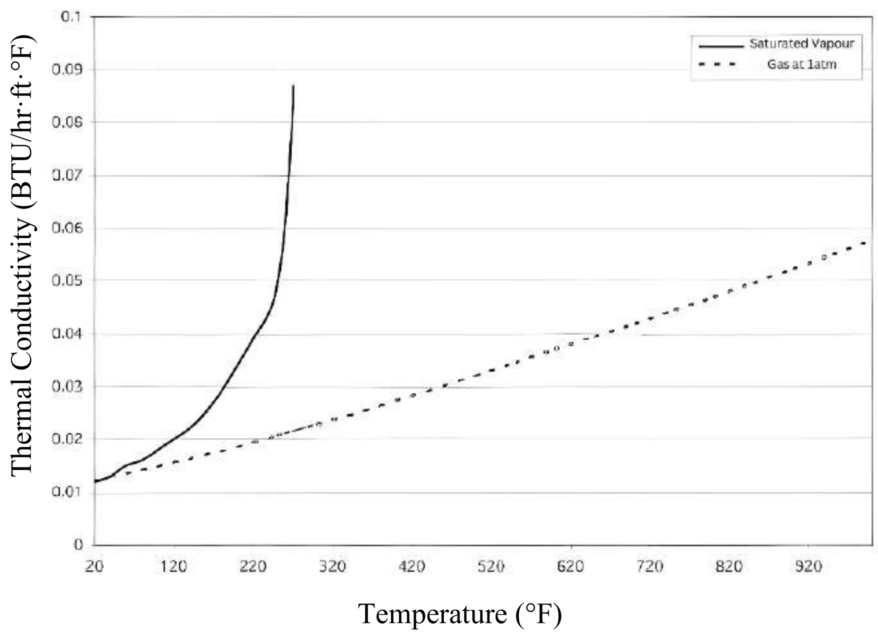

Fig. 3. Thermal Conductivity of Ammonia Gas/Vapour (Ammonia Data Book 2nd Edition, 2008)

The viscosity (μ) of ammonia, both as a liquid, is approximately average when compared to other fluids. Fig. 4 shows the following graphs for the viscosity values of ammonia in its liquid form.

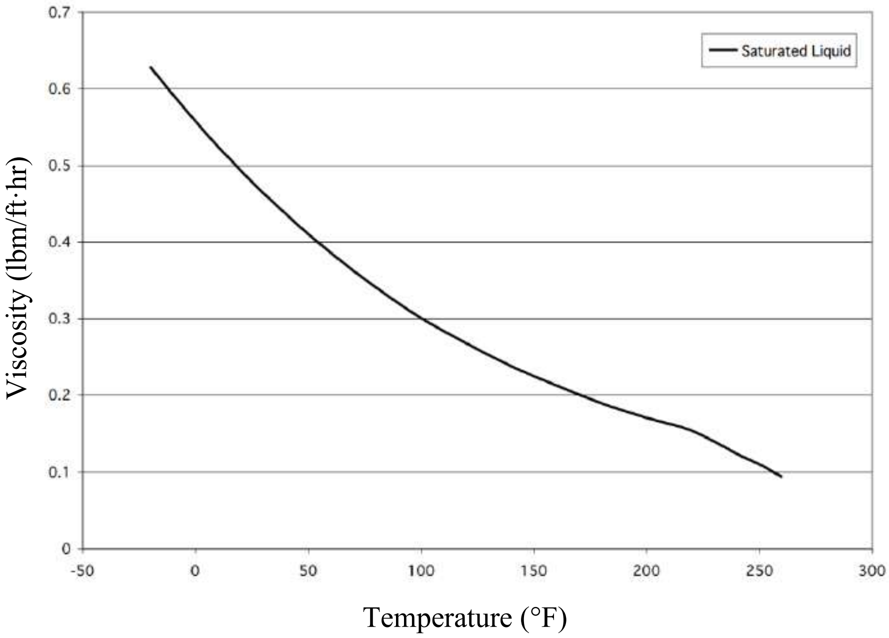

Fig. 4. Viscosity of Ammonia Liquid (Ammonia Data Book 2nd Edition, 2008)

4.3 Safety and Handling

Ammonia is widely recognised as an effective primary refrigerant due to its high efficiency and low environmental impact. However, its use comes with significant safety considerations that must be addressed to ensure safe handling and operation. Firstly, risk assessment and prevention are important. The first step in ensuring safety is to conduct a thorough risk assessment of the ammonia refrigerating system. This involves identifying potential hazards associated with ammonia, such as leaks or exposure, and implementing preventive measures to mitigate these risks. (Lamberg et al., 2015). The safety guide emphasises the importance of assessing and preventing various risks associated with ammonia systems to promote safe operation. Moreover, incident management. Effective incident management is crucial for minimising the consequences of ammonia leaks or other emergencies. The safety guide highlights the importance of having a clear plan for managing incidents, including the use of gas sensors and proper ventilation in areas where ammonia is present. This can help detect leaks early and prevent the buildup of hazardous concentrations of ammonia (Lamberg et al., 2015).

Suppliers are required to train staff in the operation and safety of ammonia refrigeration systems according to European Standard SFS-EN 378, which includes understanding equipment, following instructions, and complying with safety measures (Khudhur et al., 2022). Systems must have isolation valves to minimise hazards and leaks, gas sensors monitored at control panels for quick leak detection, and pressure relief valves on pressurised parts to prevent overpressure. Suppliers must also provide key information such as contact details, system operation instructions, refrigerant type and levels, diagrams, handling and safety procedures, PPE requirements, first aid steps, and ammonia safety data sheets. Safe operating limits, including minimum and maximum design pressures, must be set before use, ensuring no part exceeds the pressure rating of its weakest component. In case of an ammonia leak, management must have emergency protocols for detection, alarms, PPE use, evacuation, and system shutdown, with staff trained to respond quickly and safely. During a leak, follow DOSH guidelines: secure and isolate the area, evacuate upwind, use barriers and windsocks, restrict access, call trained responders, and monitor ammonia levels to manage the situation. Control rooms should be located outside the main process area, with system data linked to control panels and vibration sensors on major equipment to detect problems early (Khudhur et al., 2022).

4.4 Environmental Impact and Regulatory Context

The Total Equivalent Warming Impact (TEWI) model was employed to evaluate the carbon emissions linked to both refrigerants. The findings revealed that Ammonia's TEWI is 68.1% lower than that of R404A. This indicates that Ammonia not only offers superior energy efficiency but also substantially lowers environmental impact, positioning it as a more sustainable choice for refrigeration (Dreepaul et al., 2020).

Fig. 5 shows the CO_2 gas released into the atmosphere by refrigerants as an alternative to R22 gas. The current system using R22 gas emits approximately 95 kg of CO_2 annually. Among alternative refrigerants, R717 stands out as the one with the lowest CO_2 emissions, releasing only 78.62 kg per year from the generators. The CO_2 emissions from other refrigerants are as follows: 96.28 kg for R1234yf, 93.38 kg for R161, 87.23 kg for R245fa, 87.02 kg for R453A, and 110.7 kg for R407C. Notably, R407C is the refrigerant associated with the highest CO_2 emissions (Durmusoglu & Kocak, 2023).

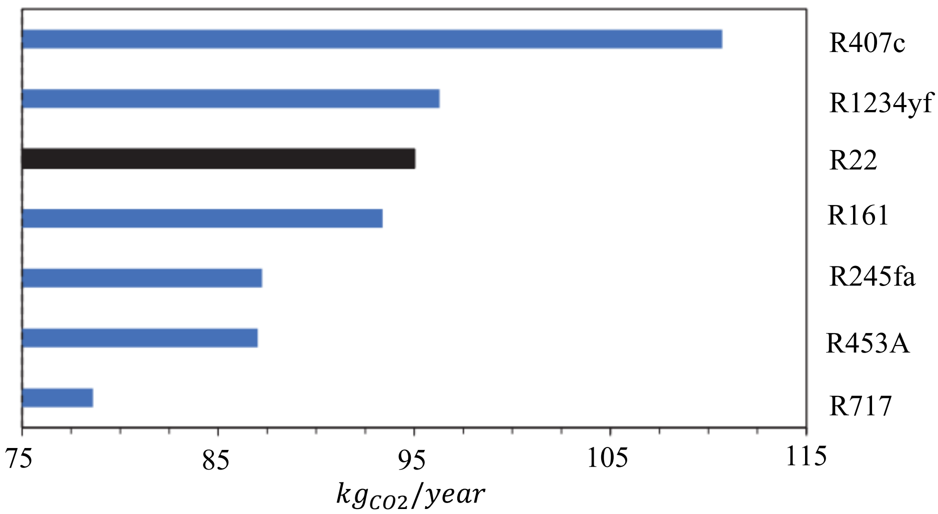

Fig. 5. CO_2 gas released to the atmosphere by refrigerants as an alternative to R22 gas. (Durmusoglu & Kocak, 2023)

5.0 SUMMARY

The article presents a detailed assessment of ammonia as a reliable and sustainable primary refrigerant for air conditioning systems, particularly considering global efforts to mitigate climate change and phase out high-GWP substances. Ammonia refrigerant (R-717), with its zero ODP and zero GWP, stands out as an environmentally friendly alternative to conventional refrigerants. It has been widely used in industrial refrigeration for over a century, with a proven track record of operational reliability and thermal efficiency. Its superior thermodynamic properties enable systems to operate with lower energy consumption and reduced operational costs. These characteristics make ammonia not only a cost-effective solution but also one aligned with future regulatory and sustainability goals. Despite its toxicity and mild flammability, the article highlights that with proper system design, handling protocols, and safety measures, ammonia-based systems can operate safely and efficiently, even in commercial and semi-commercial applications. The study also compares ammonia with HFCs, which, while chemically stable and less toxic, are associated with moderate to high GWP. HFCs continue to be used in many applications due to their compatibility with existing systems and ease of use, making them a practical choice during the transition to greener refrigerants. However, with increasing environmental regulations such as the Kigali Amendment and regional climate action policies, the use of high-GWP refrigerants like HFCs is expected to decline. The article stresses that ammonia's environmental benefits, long-term economic advantages, and compliance with future regulations make it a strong candidate for wider adoption in the air conditioning sector. Furthermore, it explores how the current regulatory context, including environmental impact assessments, supports the push for low-impact refrigerants like ammonia. In summary, while HFCs serve as convenient short- to medium-term solutions, ammonia presents a compelling case as a future-proof, eco-efficient refrigerant that supports both environmental responsibility and operational performance.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Addressing Fatigue on Cognitive and Physical Performance in Maritime Operations: A Comprehensive Review

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Abstract - Fatigue in maritime operations poses a significant threat to the cognitive and physical performance of seafarers, leading to severe safety risks and operational inefficiencies. This comprehensive review examines the multifaceted impact of fatigue on maritime personnel, focusing on cognitive impairments and physical deterioration. Long working hours, irregular schedules, and the demanding nature of maritime tasks contribute to chronic fatigue, disrupting circadian rhythms and reducing alertness. Cognitive impairments due to fatigue, including diminished decision-making abilities, slower reaction times, and decreased situational awareness, are identified as critical factors leading to navigation errors and equipment mishandling. Physically, fatigue results in reduced muscle activity, impaired proprioception, and overall motor performance decline, further exacerbating the risk of accidents. The mental health of seafarers is also significantly affected, with increased incidences of stress, anxiety, and depression linked to chronic fatigue. This review highlights the importance of implementing effective mitigation strategies, such as fatigue monitoring systems, ergonomic ship design improvements, and organizational interventions focused on better shift schedules and fatigue management training. The role of regulatory bodies in enforcing guidelines to ensure adequate rest and the potential of emerging technologies like artificial intelligence in fatigue management are also explored. By addressing the causes, impacts, and mitigation strategies of fatigue, this review aims to enhance the safety, performance, and well-being of seafarers, ultimately contributing to the overall efficiency and safety of maritime operations.

Keywords: Fatigue Mitigation Strategies, Maritime Fatigue, Maritime Operations, Occupational Health, Seafarer safety.

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1.0 INTRODUCTION

Maritime operation fatigue poses a significant concern as it directly impacts the safety, performance, and well-being of seafarers. This fatigue stems from factors such as long working hours, irregular schedules, and the demanding nature of maritime tasks. The combination of these elements creates an environment where seafarers are highly susceptible to fatigue, which in turn, can lead to reduced alertness and an increased risk of accidents. As highlighted by Jepsen et al. (2015), the unique working conditions at sea exacerbate the prevalence of fatigue, making it a critical issue that needs to be addressed within the maritime industry.

The nature of maritime work, characterized by extended hours, unpredictable schedules, and significant physical demands, significantly contributes to the high levels of fatigue experienced by maritime personnel. This multifaceted issue requires a comprehensive understanding to develop effective mitigation strategies. Researchers such as Andrei et al. (2020) and Phillips (2015) emphasize the importance of recognizing the various factors contributing to maritime fatigue to implement measures that can enhance the well-being and operational efficiency of seafarers. By addressing these factors, it is possible to improve safety and performance standards within the maritime sector.

2.0 CAUSES OF MARITIME OPERATION FATIGUE

Several factors contribute to fatigue in maritime operations. Extended working hours and lack of adequate rest are primary contributors (Johnson & Lipscomb, 2006). Seafarers often face irregular sleep patterns due to shift work, which disrupts their circadian rhythms (Youn & Lee, 2020). The physically demanding nature of maritime tasks further exacerbates fatigue levels (Moray, 2021). Fig. 1 shows how different perceptions of standard working hours affect productivity, suggesting potential links to fatigue levels (Vallo & Mashau, 2020).

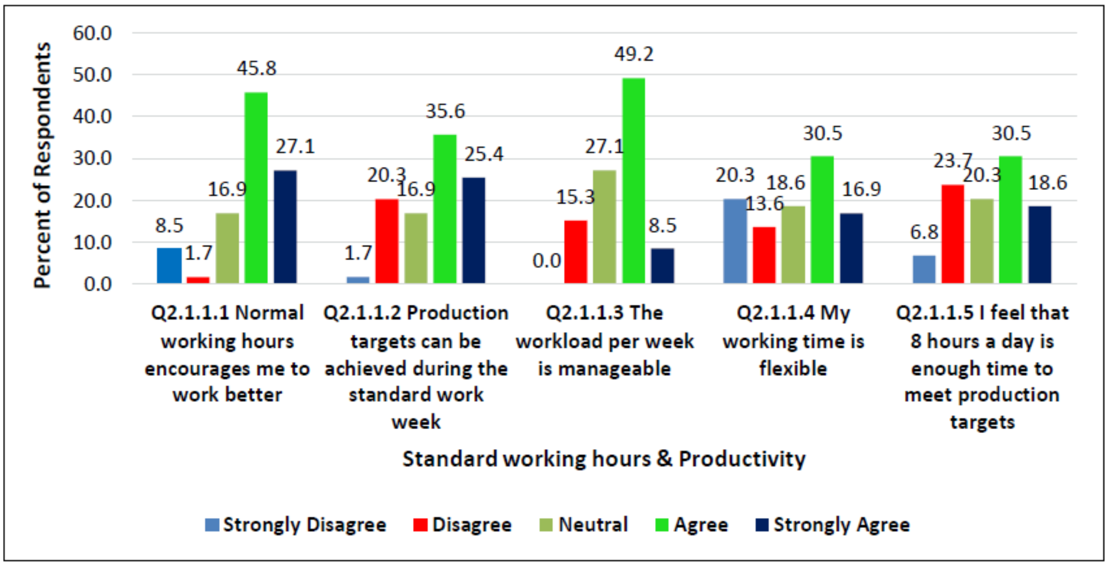

Fig. 1. Impact of Working Hours on Fatigue Levels (Vallo & Mashau, 2020).

Studies have shown that seafarers working over 12 hours a day are significantly more likely to experience fatigue-related issues (Allen et al., 2008). Moreover, the quality of rest periods between shifts is often insufficient to counteract the effects of long working hours (Grech, 2016). The interplay between these factors creates a complex fatigue landscape in maritime operations (Monteiro et al., 2020).

3.0 IMPACTS OF FATIGUE ON MARITIME OPERATIONS

Fatigue in maritime operations has profound implications for both individuals and the industry at large. It significantly impairs cognitive functions, reducing alertness and increasing the likelihood of errors (Ma et al., 2023). This can lead to accidents, posing safety risks not only to seafarers but also to the marine environment (Ghosh & Daszuta, 2019).

Research indicates that fatigue is a contributing factor in a significant number of maritime accidents (Galieriková et al., 2020). Cognitive impairments due to fatigue affect decision-making abilities, reaction times, and overall situational awareness (Riethmeister et al., 2018). These impairments increase the risk of navigation errors, equipment mishandling, and other operational failures (Hetherington et al., 2006). Fig. 2 indicated fatigue correlates with decreased muscle activity, impaired proprioception, and cognitive function interference affecting motor performance (Abd-Elfattah et al., 2015).

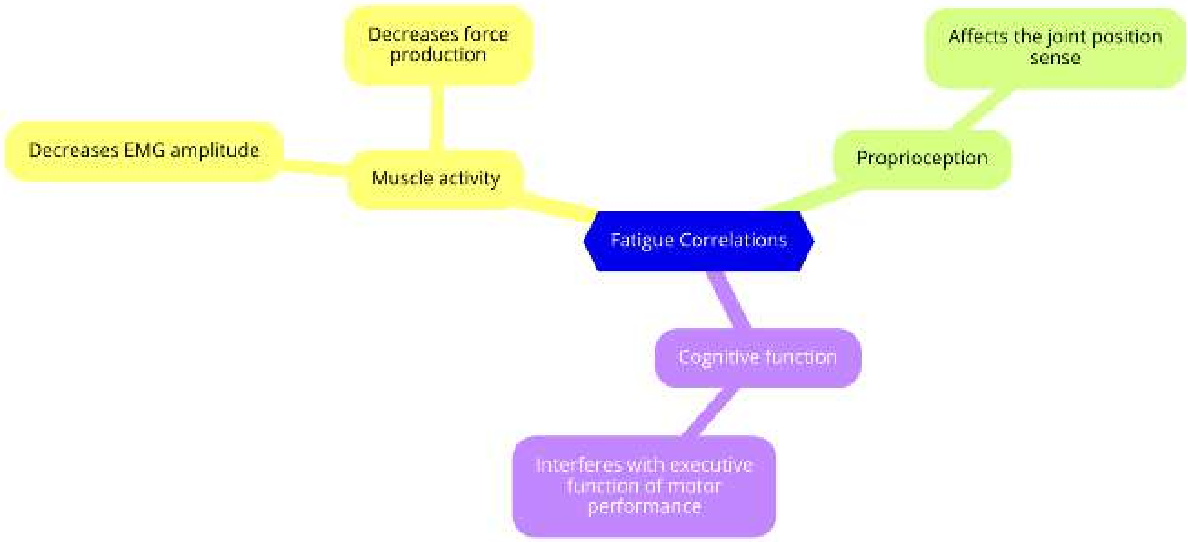

Fig. 2. Cognitive Impairments Due to Fatigue (Abd-Elfattah et al., 2015).

Furthermore, fatigue impacts the mental health and well-being of seafarers, leading to issues such as stress, anxiety, and depression (Carotenuto et al., 2012). Long-term exposure to high fatigue levels can result in chronic health conditions, reducing the overall life quality of maritime workers (Roberts & Marlow, 2005). These health issues not only affect individuals but also lead to increased absenteeism and reduced productivity (Koopman et al., 2002).

4.0 MITIGATION STRATEGIES

Addressing maritime operation fatigue requires a multifaceted approach involving policy changes, technological advancements, and organizational interventions (Monteiro et al., 2020). Regulatory bodies such as the International Maritime Organization (IMO) have set guidelines to limit working hours and ensure adequate rest (International Maritime Organization (IMO), 2019). However, compliance and enforcement remain challenges (Berg, 2013).

Technological solutions, such as fatigue monitoring systems, are emerging as effective tools to manage fatigue (Sanquist et al., 1997). These systems use biometric data to assess fatigue levels and alert personnel when they are at risk (Thomas et al., 2019). Additionally, ergonomic improvements in ship design can reduce physical strain and enhance the comfort of seafarers (Kompier, 2006).

Organizational strategies, such as improving shift schedules and providing better training on fatigue management, are also essential (Allen et al., 2007). Creating a culture that prioritizes health and well-being can help mitigate the negative impacts of fatigue (Zhao et al., 2020). Employers should encourage practices that promote good sleep hygiene and regular physical activity (Arslan et al., 2019).

5.0 FUTURE RESEARCH DIRECTIONS

Despite significant progress, there are still gaps in understanding and managing maritime operation fatigue. Future research should focus on developing more precise measurement tools for fatigue (Williamson et al., 2011). Longitudinal studies examining the long-term health effects of maritime fatigue are needed to inform policy and practice (Oldenburg et al., 2010).

Interdisciplinary research involving psychology, occupational health, and engineering can provide deeper insights into fatigue mechanisms and mitigation strategies (Wadsworth et al., 2008). Additionally, exploring the role of emerging technologies such as artificial intelligence in fatigue management could offer innovative solutions (Ziakkas et al., 2024).

Policymakers and industry leaders must collaborate to implement evidence-based strategies and continuously evaluate their effectiveness (Simkuva et al., 2016). By prioritizing research and innovation, the maritime industry can enhance safety, performance, and the well-being of its workforce (Acciaro & Sys, 2020).

6.0 CONCLUSION

Fatigue in maritime operations is a critical issue that significantly affects both cognitive and physical performance of seafarers. The causes of fatigue are multifaceted, encompassing long working hours, irregular shift patterns, and high job demands that disrupt sleep and circadian rhythms. This cumulative sleep debt and disrupted biological clock not only diminish alertness and cognitive function but also increase the risk of accidents and adverse health outcomes. Recognizing these factors is essential for stakeholders to develop targeted interventions aimed at mitigating fatigue and its detrimental impacts.

To effectively address maritime fatigue, it is crucial to implement comprehensive solutions that involve regulatory changes, technological advancements, and enhanced crew management practices. Strategies such as optimizing shift schedules, ensuring adequate rest periods, and promoting a healthy work-life balance can significantly reduce fatigue levels. Additionally, fostering a collaborative approach among maritime organizations, researchers, and policymakers will drive continuous improvement and innovation in this area. Continued research and interdisciplinary collaboration are vital to developing robust, evidence-based interventions that enhance the safety and well-being of seafarers, ultimately leading to safer and more efficient maritime operations.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Smart Steering Gear Oil Level Monitoring System for Maritime Vessels

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Abstract - The steering gear system on ships plays a vital role in navigation and manoeuvrability, utilising a hydraulic mechanism to move the rudder. For the system to operate safely and reliably, it is essential to maintain the hydraulic oil level in the reservoir at the correct level. This journal article describes the design and development of an automatic top-up system for the steering gear oil tank, using the PIC16F84A microcontroller. Float sensors continuously monitor the oil level, while a pair of pumps is used to top up the oil when required. The system offers a cost-effective and efficient solution to enhance operational safety and reduce reliance on manual monitoring. The microcontroller was selected for its simplicity, reliability, and suitability for marine automation applications.

Keywords: Alarm system, Hydraulic oil, Microcontroller, Steering gear system, Tank level control

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1.0 INTRODUCTION

The steering gear system in maritime vessels relies on hydraulic mechanisms for efficient navigation and rudder control. Effective hydraulic operation is fundamentally dependent on maintaining the oil level within a designated operational range. In most vessels, oil levels are assessed and replenished manually, a procedure that can be unreliable and labour-intensive. Inaccuracies in monitoring or delays in replenishment may reduce steering efficacy, presenting safety hazards during navigation. Any drop in oil levels may result in steering failure, potentially leading to serious maritime incidents (IMO, 2009). To address this issue, the automation of the oil replenishment process is proposed using a microcontroller-based system. Automation in marine hydraulic systems has become an area of growing interest, aiming to reduce accidents and improve reliability (Ahmed et al., 2021; Singh & Tan, 2024). The PIC16F84A microcontroller is selected for its simplicity, accessibility, and suitability for embedded control applications. The proposed system maintains the oil level within safe operating limits by integrating oil level sensors and automated pump control via the microcontroller. This approach not only reduces dependence on manual inspections but also enhances the durability and reliability of the hydraulic system. This research demonstrates that a basic microcontroller-based system can efficiently automate oil level regulation in a steering gear reservoir. The use of the PIC16F84A ensures cost-effective and resilient implementation with minimal power and hardware requirements (Kim & Lee, 2015). Automating the refilling process mitigates the challenges associated with manual monitoring, particularly on older vessels or in remote operational environments. The design allows for effortless scaling and customisation and can be integrated with alarm systems or display modules to enhance functionality. AI-based anomaly detection improves real-time alerts and responses in lubrication systems (Singh & Tan, 2024). Future developments may include the incorporation of GSM (Global System for Mobile Communication) modules for remote alerts or the incorporation of data logging functionalities for maintenance monitoring. The efficacy of this prototype indicates potential wider applications in industrial fluid management systems outside maritime contexts.

The diagram Fig. 1. illustrates an electro-hydraulic steering gear system commonly used on board ships, consisting of two independent power units to ensure redundancy and reliability.

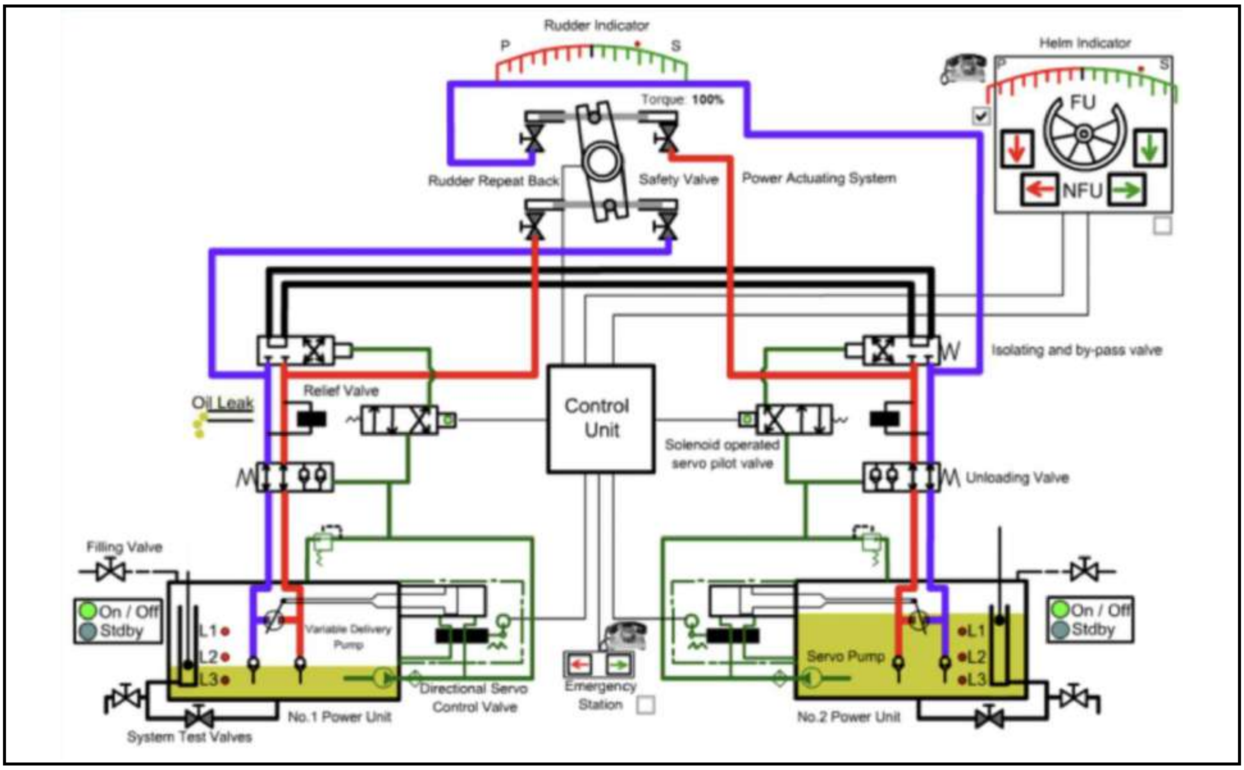

Fig. 1. Steering gear system.

2.0 IMPORTANT INFORMATION

The dependability of steering gear systems in marine and industrial contexts is essential for operational safety and efficacy, particularly in systems that utilise hydraulic actuation. These systems require a regular and sufficient supply of hydraulic oil to ensure seamless and continuous functioning. Traditionally, oil level monitoring and replenishment are performed manually, a practice that may lead to delays, human error, or oversight, ultimately reducing system efficiency or increasing the risk of failure. Such failures, often caused by inadequate maintenance or undetected leaks, may result in the steering gear seizing, which in turn could lead to vessel collision or grounding. (IMO, 2009; DNV, 2022). Numerous cases of maritime steering gear failures have been attributed to insufficient hydraulic fluid levels (Chang & Sun, 2023).

This research outlines the design and implementation of an automated oil tank filling system controlled by the PIC16F84A microcontroller. The system employs digital float sensors to monitor oil levels and a microcontroller-based pump control mechanism that initiates the filling process when low oil levels are detected and halts operation once the optimal level is reached. The integration of this automatic control system can reduce operational downtime caused by oil level issues and improve overall maintenance efficiency. An automated solution for monitoring and regulating oil levels in the hydraulic tank is essential for enhancing operational safety and ensuring compliance with classification standards. (Bureau Veritas, 2023).

The selection of the PIC16F84A microcontroller is based on its simplicity, affordability, and suitability for embedded control applications in fluid management systems. In addition, fault-tolerant and redundant designs ensure that the system remains operational even in the event of component failure (Wei and Hassan, 2023; Zhao and Liu, 2017). This study examines the hardware architecture, software algorithms, and testing outcomes of the proposed system, with the objective of advancing the

ISSN: 2590-345 e-ISSN: 2976-3843

development of cost-effective and efficient automation solutions in maritime hydraulic support systems. Recent advancements in maritime hydraulic automation suggest that sensor-based monitoring systems help mitigate maintenance risks and support predictive failure detection. (Ali & Chen, 2022; Patel & Wang, 2021).

3.0 PROCEDURE

The methodology begins with the development of a control algorithm that processes input from two float-type sensors: one indicating a low oil level and the other indicating a critically low oil level. These sensors transmit digital LOW or LOW LOW signals to the input pins (RA1 and RA0) of the PIC16F84A microcontroller. When the oil level falls below the lower sensor, the microcontroller activates the relay via output pin RA0, which in turn starts the pump to replenish the tank. Simultaneously, the buzzer is triggered to provide an audible alert.

Upon the LOW sensor clear, the pump ceases operation. A debouncing technique is employed to eliminate false activations caused by sensor noise. The microcontroller successfully activates the steering gear shutdown relay even under LOW LOW level conditions. This demonstrates that the steering gear complies with the redundancy requirements set by the International Maritime Organization (IMO, 2020). The operation is also connected to an LCD for ease of monitoring and provides real-time system information. The control circuit includes LEDs configured to indicate the system status.: LOW LEVEL, LOW LOW LEVEL, and NORMAL.

3.1 System Flow

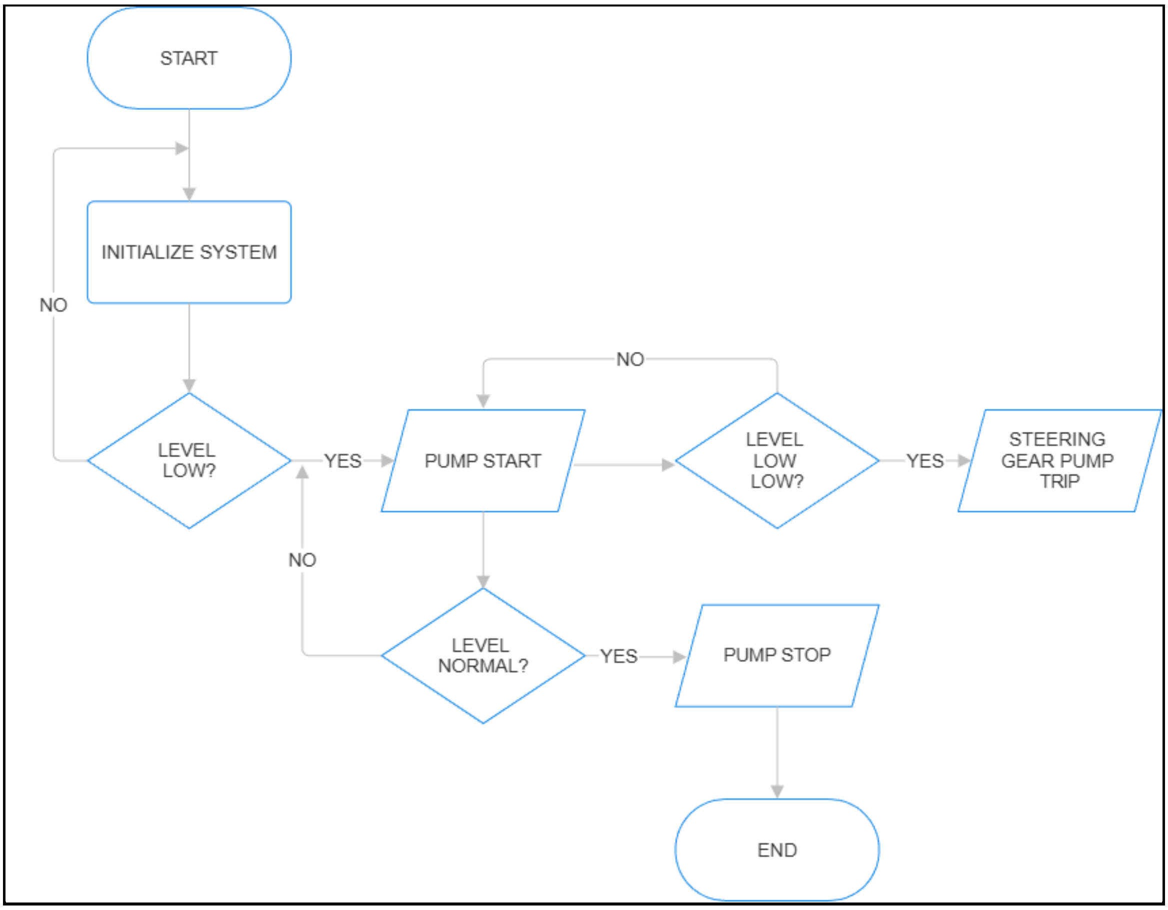

Fig. 2. Flowchart of automatic oil tank top up.

The flowchart illustrates the automatic oil tank top-up system used in steering gear and other hydraulic systems to maintain the correct oil level in the reservoir. The process begins with system initialisation, ensuring that all sensors, valves, and control logic are prepared for operation. Once initialised, the system continuously monitors the oil level in the tank. If the oil level is detected to be low, the control logic activates the top-up pump, which supplies oil from a storage tank to the main system reservoir. As the pump operates, the oil level rises until it reaches the normal operating level, at which point the control system automatically stops the pump to prevent overfilling. If the system detects that the oil level drops further below a critical threshold, indicated as “Level Low Low”, it signifies a serious leak or malfunction. In such cases, the system immediately trips the steering gear pump to prevent damage to the hydraulic system and to avoid air ingress into the circuit. This automatic top-up arrangement ensures that the hydraulic system maintains a safe and sufficient oil level at all times, reducing the need for manual intervention. It enhances operational safety and reliability, ensuring continuous steering capability while protecting pumps and other components from running dry due to oil loss.

Table 1. Truth table show how sensor input value correspond to specific system response

Operation Mode	Low Level	Normal Level	Low Low Level
Oil Pump Running	1	0	1
Steering Gear Pump Trip	0	0	1
Buzzer	1	0	1

Table 1 presents the logical relationship between the sensor input values and the corresponding system responses in the automatic oil tank filling system for the steering gear.

The binary states ‘1’ and ‘0’ denote the active (ON) and inactive (OFF) conditions of each component respectively, under various oil-level scenarios: Low Level, Normal Level, and Low-Low Level. Under the Low Level condition, the oil pump is activated to initiate refilling, and the buzzer is energised to alert the operator to the low oil level. The steering gear pump remains in operation, as the oil supply is still within a safe margin.

Under the Normal Level condition, all outputs remain inactive. This indicates that the oil level is adequate; therefore, no corrective action or alarm signal is required. When the system detects a Low-Low Level, a critically low condition is reached. The oil pump continues to operate to replenish the oil, and the buzzer remains active to provide a high-priority warning. Concurrently, the steering gear pump is automatically tripped to prevent mechanical damage resulting from insufficient lubrication. This control sequence ensures reliable oil level regulation, improves operational safety, and protects the steering gear system from potential failure caused by inadequate oil supply.

3.2 Main Components

- **Microcontroller**: A microcontroller is selected for its processing power and compatibility with various sensors.

- **Sensors:** Float type water level sensors to monitor tank levels

-**Pumps:** Automatic pumps to carry out auto oil top up for tank process

-**Liquid Crystal Display:** Monitoring and info for operator

-**Buzzer:** Indication with sound if got low level alarm

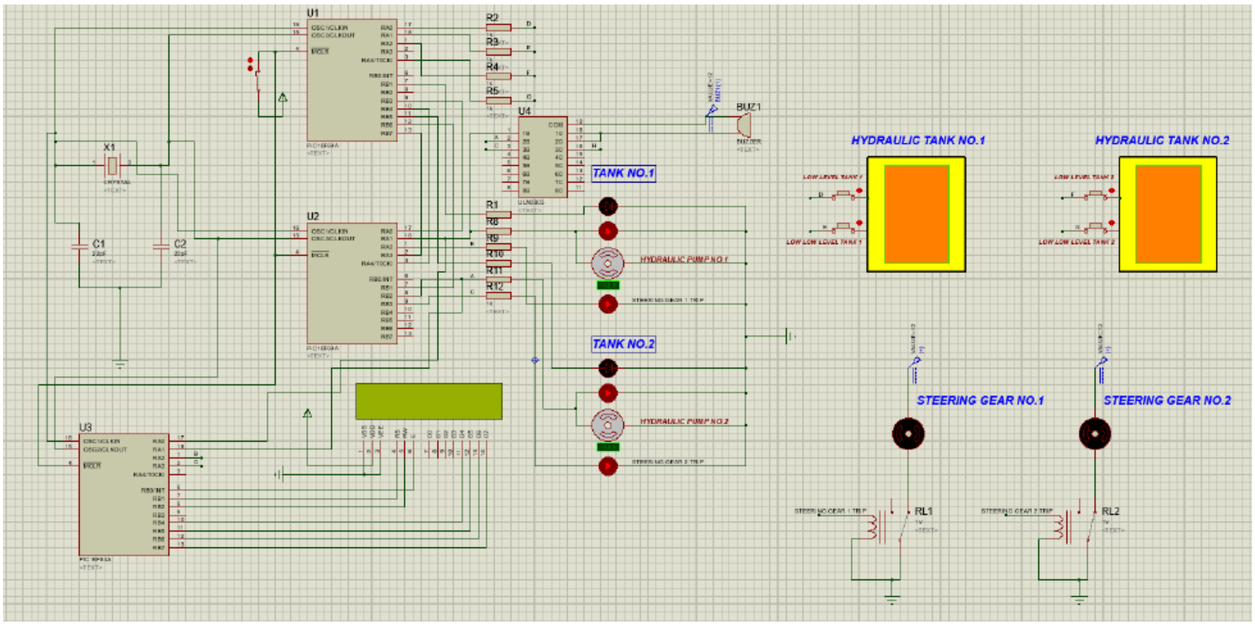

Fig. 3. Displays the Proteus environment used to simulate the system.

4.0 RESULTS AND ANALYSIS

The system accurately identified LOW and NORMAL oil levels with a switching latency of less than one second, demonstrating a rapid response to changes in fluid level. The relay control functioned reliably and did not overheat or produce noise. LED indicators provided accurate feedback on the current system status. Throughout testing, the oil filling procedure operated smoothly, with no false triggers observed during 24 hours of continuous operation. The PIC16F84A performed effectively despite its limited input and output capacity and memory. The entire system was cost-effective and straightforward to assemble using readily available components. Some limitations were noted, such as the absence of real-time logging and the lack of a wireless alert mechanism. These aspects are currently under consideration for future enhancements. The integration of Internet of Things (IoT) enabled predictive maintenance modules may be explored in forthcoming developments. (Ali & Chen, 2022; Patel & Wang, 2021).

Table 2. Sensor Trigger Response Time and Pump Operation Duration

Test Cycle	Low Level Detected	Normal Level Detected	Pump Run Time (s)
1	Yes	Yes	15
2	Yes	Yes	14
3	Yes	Yes	16
4	Yes	Yes	15
5	Yes	Yes	14

Table 2 presents the results of five test cycles conducted to evaluate the sensor trigger response time and the pump operation duration during the automatic oil filling process. The test verifies the system’s ability to accurately detect both Low Level and Normal Level oil conditions and to activate the pump for an appropriate duration.

Throughout all five test cycles, both the Low Level and Normal Level sensors consistently detected their respective conditions, indicating reliable sensor performance and stable signal response. This

consistency demonstrates that the sensors are properly calibrated and capable of detecting level changes without delay or signal interference.
The pump run time ranged between 14 and 16 seconds, with a calculated mean duration of 14.8 seconds and an estimated standard deviation of ±0.84 seconds. This minor variation is within acceptable operational tolerance and may be attributed to small differences in oil flow rate, tank geometry, or sensor sensitivity.
Overall, the results confirm that the system demonstrates accurate sensor triggering, consistent pump activation, and stable control performance. The oil pump successfully operates upon detection of a low oil level and stops once the normal level is restored, ensuring effective and automatic regulation of oil levels within the steering gear reservoir.

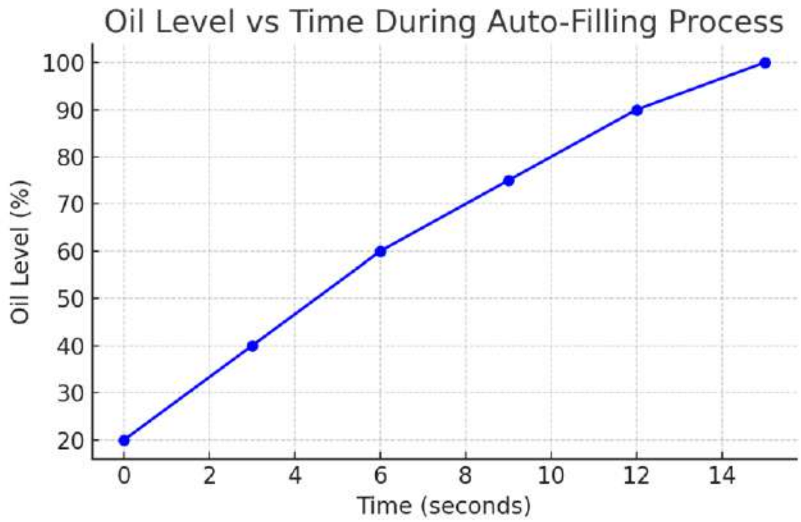

Fig. 4. Oil Level vs Time During Auto-Filling Process

Figure 4 illustrates the variation in oil level percentage with respect to time during the automatic oil-filling process. The graph demonstrates a steady and progressive increase in oil level, indicating that the system responds effectively once the Low-Level sensor is triggered and continues filling until the Normal-Level condition is reached. At the initial time (t = 0 s), the oil level is approximately 20 per cent, corresponding to the low-level detection point. As the oil pump activates, the oil level rises rapidly, reaching approximately 40 per cent at 3 seconds, 60 per cent at 6 seconds, and 75 per cent at 9 seconds. The rate of filling begins to gradually decrease beyond this point, as shown by the reduced slope between 9 and 15 seconds, where the oil level ultimately attains 100%. This trend indicates that the pump maintains a consistent delivery rate in the early phase of operation, followed by a slight reduction in flow rate as the tank nears full capacity. The slowing rate is likely caused by the increasing back pressure within the reservoir or by the pump control circuit adjusting output near the upper level limit. Overall, the results confirm that the automatic oil-filling mechanism operates efficiently and reliably, with a total filling duration of approximately 15 seconds, consistent with the data presented in Table 2. The smooth and continuous rise in oil level further validates the sensitivity and accuracy of the level sensors and the stability of the control logic implemented in the system.

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This LCD showing when both pump in normal operation which one or both steering gear run and oil pump stop.

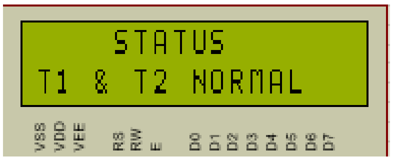

Fig. 5. LCD Display Output During Normal Condition

This LCD showing when tank 1 got low level alarm and the oil top up pump running for no 1 tank. The steering gear pump no 1 still running while the oil been top up.

Fig. 6. LCD Display Output During Tank 1 Low Level Condition

This LCD showing when tank 2 got low level alarm and the oil top up pump running for no 2 tanks. The steering gear pump no 2 still running while the oil been top up.

Fig. 7. LCD Display Output During Tank 2 Low Level Condition

This LCD showing when tank 1 got low low level alarm and the oil top up pump running for no 1 tank. The steering gear pump no 1 tripped while the oil been top up.

Fig. 8. LCD Display Output During Tank 1 Low Low Level Condition

This LCD showing when tank 2 got low low level alarm and the oil top up pump running for no 2 tank. The steering gear pump no 2 tripped while the oil been top up.

Fig. 9. LCD Display Output During Tank 2 Low Low Level Condition

This LCD showing when both oil tank got low low level alarm and the oil top up pump running for both tank. The steering gear pump no 1 and 2 tripped while the oil been top up.

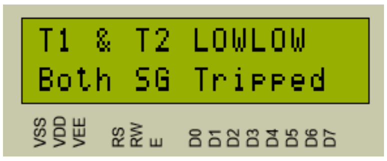

Fig. 10. LCD Display Output During Tank 1 and 2 Low Low Level Condition

5.0 DISCUSSION AND CONCLUSION

This research demonstrates that a basic microcontroller-based system can efficiently automate oil level regulation in a steering gear reservoir. The utilisation of the PIC16F84A ensures a cost-effective and resilient implementation with minimal power and hardware requirements. Automating the refilling process mitigates the challenges associated with manual monitoring, particularly on older vessels or in remote operational environments. The design supports effortless scaling and customisation and can be integrated with alarm systems or display modules to enhance functionality. Future developments may include the utilisation of GSM modules for remote notifications or the integration of data logging capabilities for maintenance tracking. The effectiveness of this prototype suggests potential broader applications in industrial fluid management systems beyond maritime contexts.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Akademi Laut Malaysia Melaka for their support in developing and testing this project. Special thanks to the marine workshop technicians for providing access to test equipment and simulation facilities.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Automatic Water Refill System for Chemical Dosing Tanks Using Float Sensors and Microcontroller

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Abstract - This paper presents the development of an intelligent water refill system designed for a chemical dosing tank using a microcontroller-based electronic circuit. The system is equipped with four strategically placed float sensors that monitor the water level within the tank. A water pump, controlled by the microcontroller, regulates the flow of distilled water into the tank. When the water level drops to the lower float, the system activates the pump to begin refilling. Once the upper float is reached, the pump is automatically shut off to prevent overfilling. Additionally, the lowest float functions as a critical low-level alarm, and the highest float serves as a high-level alarm, both triggering LED and buzzer warnings. This design automates manual processes, improves system reliability, and minimises human intervention. The integration of electronic controls ensures timely refills and safeguards against tank dry-out, which is essential for consistent chemical dosing performance. The system also includes a manual override switch for pump control in the event of automation failure. Its compact design and low cost make it suitable for industrial and laboratory environments where water level management is critical.

Keywords: Chemical dosing, Float sensors, Microcontroller, Water pump, Water level control

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1.0 INTRODUCTION

Chemical dosing systems are widely used in industrial and laboratory applications to accurately dispense controlled amounts of chemicals into process streams (Turner & Hassan, 2023). These systems often rely on a steady supply of distilled water for proper dilution and smooth operation (Blink & Cho, 2022). In many cases, especially where small-capacity tanks are used, the refilling of water is conducted manually. While this approach is simple, it introduces various inefficiencies and operational risks (Rahman et al., 2021).

Manual filling tasks require constant human attention, which can be time-consuming and susceptible to errors. Overflow may occur if the filling valve is left open and unattended, while a delayed refill could result in the tank running dry (Muhammad et al., 2024). Both scenarios have the potential to damage dosing equipment or disrupt the chemical dosing process. Furthermore, chemical overspill may lead not only to wastage but also to safety risks arising from possible chemical reactions outside the tank (Polymaster, 2023; Blue White® Industries, 2024). With the growing emphasis on automation and system reliability, there is a need to enhance such processes through embedded system-based solutions that minimise dependence on human supervision (Bhatt et al., 2021)

Amerzine, an oxygen scavenger, removes dissolved oxygen from boiler feedwater to prevent pitting corrosion, while SLCC-A, a corrosion inhibitor, forms a protective film on metal surfaces to reduce general corrosion (Drew Marine, 2023). Although these treatments could technically be combined, separate dosing systems are maintained to ensure optimal chemical performance, prevent unwanted interactions, and allow precise control of each treatment process.

This paper presents an intelligent water refill system for chemical dosing tanks, incorporating float sensors and a microcontroller-based control circuit to automate water level monitoring and pump activation (Microchip Technology Inc., 2001; Wang & Zhang, 2020). The system is designed to ensure timely refilling, prevent overflow and dry-run conditions, and enhance overall operational efficiency. It also features a physical manual switch connected to the same circuit, enabling direct pump control in case of automation failure. The setup is implemented on two identical tanks, each serving Boiler Amerzine and Boiler SLCC-A, respectively

1.1 Objective

The primary objective of this project is to develop and implement an automated water refill system for chemical dosing tanks. The system utilises four float sensors to detect water levels and a dedicated pump to refill the tank when required (Sure Instrument, 2020). The design aims to ensure consistent water availability, minimise human error, and safeguard equipment by preventing dry-run and overflow conditions. Ultimately, the goal is to enhance reliability, safety, and operational productivity across two chemical tanks through a parallel control circuit system.

1.2 Problem Statement

The existing manual method for refilling chemical dosing tanks has proven to be inefficient and unreliable (Rahman et al., 2021). Operators must frequently attend to the system to perform refilling, which is not only time-consuming but also susceptible to being overlooked during busy operations. Instances of unattended filling often result in tank overflow, while delays in refilling may cause the dosing pump to run dry. This can lead to mechanical damage, reduced dosing accuracy, and operational interruptions.

Moreover, overflow incidents may result in chemical spillage, posing hazards such as exposure to harmful substances or unintended chemical reactions outside the tank (Polymaster, 2023). In the case of strong chemicals such as sodium hydroxide, such exposure may cause skin irritation or inhalation risks (National Institute for Occupational Safety and Health [NIOSH], 2022). Therefore, a more intelligent and automated solution is required to address these persistent issues effectively. The updated design now incorporates a distilled water pump and includes manual override control in the event of system failure.

2.0 LITERATURE REVIEW

This section summarises previous studies and technologies related to chemical dosing systems, automated level control, and microcontroller-based process management, establishing the foundation for the proposed intelligent refill system.

2.1 Overview of Chemical Dosing Systems

Chemical dosing systems are used in industrial and marine settings to ensure precise delivery of treatment chemicals. These systems depend on consistent water levels for accurate dosing. Manual refilling often leads to inefficiencies such as overflow, pump dry-run, or chemical spillage, which affect process reliability.

2.2 Automation in Water Level Control

Automation in liquid level management improves accuracy, safety, and efficiency. Float sensors and electronic switches are commonly applied to control pumps and valves, reducing human error. The integration of microcontrollers further enhances responsiveness and reliability in level monitoring systems.

2.3 Microcontroller-Based Fluid Management Systems

Microcontrollers provide an effective and low-cost means of real-time control in fluid systems. They process sensor inputs and regulate outputs automatically to maintain desired levels. Prior studies in wastewater and boiler applications demonstrate their effectiveness in achieving stable, intelligent, and fail-safe operation.

2.4 Summary of Findings

Literature indicates that automated level control improves efficiency and safety. However, few designs specifically address the needs of chemical dosing tanks, where material compatibility and compactness are crucial. This project aims to bridge that gap through a tailored, intelligent refill system.

3.0 METHODOLOGY

3.1 System Design and Implementation

This project involves the development of an intelligent refill system specifically designed for chemical dosing tanks using a microcontroller-based circuit and float sensors. The system's function is to automate the distilled water refilling process, which was previously performed manually and often resulted in operational inefficiencies, such as overflow or pump dry-run conditions.

The solution is implemented through the integration of four float sensors positioned at different water levels within each tank. These sensors communicate with a control circuit that operates a distilled water pump responsible for regulating inlet water flow. When the water level drops to a defined threshold, the pump is triggered to start, allowing water to enter the tank. Once the upper level is reached, the pump automatically stops, thereby preventing overfilling. A manual switch is also incorporated into the circuit, enabling the operator to activate the pump manually in the event of automation failure. The system further includes a low-level alarm function with a buzzer and visual indicators to alert the operator if the refill fails or the tank reaches a critically low level.

This automation is designed to improve reliability and reduce human intervention in the refilling process. It also serves as a cost-effective and compact solution suitable for small-scale dosing systems used in industrial and laboratory environments. The key advantage of this system lies in its simplicity, adaptability, and its ability to safeguard the dosing pump from operational damage caused by water shortages. Furthermore, the prevention of overspill reduces chemical wastage and the associated health and safety risks, particularly for corrosive or reactive chemicals such as sodium hydroxide.

The intelligent refill system has been implemented on two separate but identical dosing tanks, one for Boiler Amerzine and one for Boiler SLCC-A, each with its own dedicated control setup but using the same operational design.

3.2 System Development Procedures

The system design reference establishes the foundation for integrating float-based level detection with microcontroller control logic to automate the water refill process. Drawing from existing industrial and marine systems, the design approach emphasises operational reliability, chemical resistance, and adaptability to the dosing tank environment. The following subsections compare the design to similar systems and explain the selection of compatible materials.

3.2.1 Functional Comparison to Sewage Treatment Plant

The research and development phase of this project drew insights from a functionally similar onboard system: the sewage treatment plant (STP) (IMO, 2017). In such systems, float sensors are employed to manage fluid levels, albeit with different operational logic. The upper float sensors are configured to activate a discharge pump to empty the tank upon reaching a high level (Flowline, 2022b). In contrast, the system developed in this project reverses that function by using float sensors to trigger a refilling mechanism via a pump rather than initiating discharge. This required careful reconfiguration of the control sequence while preserving a similar wiring arrangement and microcontroller-based architecture. A thorough understanding of the logic underpinning the STP system was essential to appropriately adapt and reprogramme the control circuit for the refill application.

3.2.2 Material Compatibility

Material selection played a critical role in system design. Since the float sensors and internal tubing come into direct contact with chemical solutions, including potentially corrosive substances like sodium hydroxide, all materials were chosen to be chemically resistant and non-reactive (National Storage Tank, Inc., 2023). The materials are comparable to those used in marine hot well systems, but were specifically sized and selected to match the dimensions and capacity requirements of the dosing tank (McMaster Carr, 2024). This ensures safe, reliable operation and consistent water levels while preventing hazardous spills or reactions during use.

3.3 Component Integration and System Logic

The integration phase combined both hardware and software elements to create a functional automated refill system. The design process involved selecting compatible components, ensuring proper interfacing between sensors and the microcontroller, and developing a logical control sequence for safe and efficient operation. The following subsections outline the hardware configuration, programming approach, and operational logic in detail.

3.3.1 Hardware Components

The system uses the following components:

- Microcontroller: PIC16F84A
- Float Sensors: Mechanical float switches (4 units), each positioned at different water levels
- Distilled Water Pump: Used to control water inflow
- Power Supply: 12V DC source
- Indicators and Alarms: Visual (LED) and audio (buzzer) alerts
- Manual Switch: Connected in parallel to the pump circuit for emergency use

3.3.2 Software and Programming

The system design and simulation were conducted using Proteus version 8. The microcontroller was programmed using the PIC C Compiler, enabling conditional logic based on float sensor inputs (Ding & Shi, 2019).

3.3.3 Operational Logic

Figure 1 shows the float sensors dictate the pump's operation as follows (Flowline, 2022b):

- The pump activates when the water level is low (Float 2 triggered) and stops when the high float (Float 3) is reached.
- If the water level drops below the lowest float (Float 1), an alarm is activated to alert the operator.
- If the highest float (Float 4) is triggered, an overflow alarm is activated.
- A manual switch allows direct control of the pump in case of automation failure.

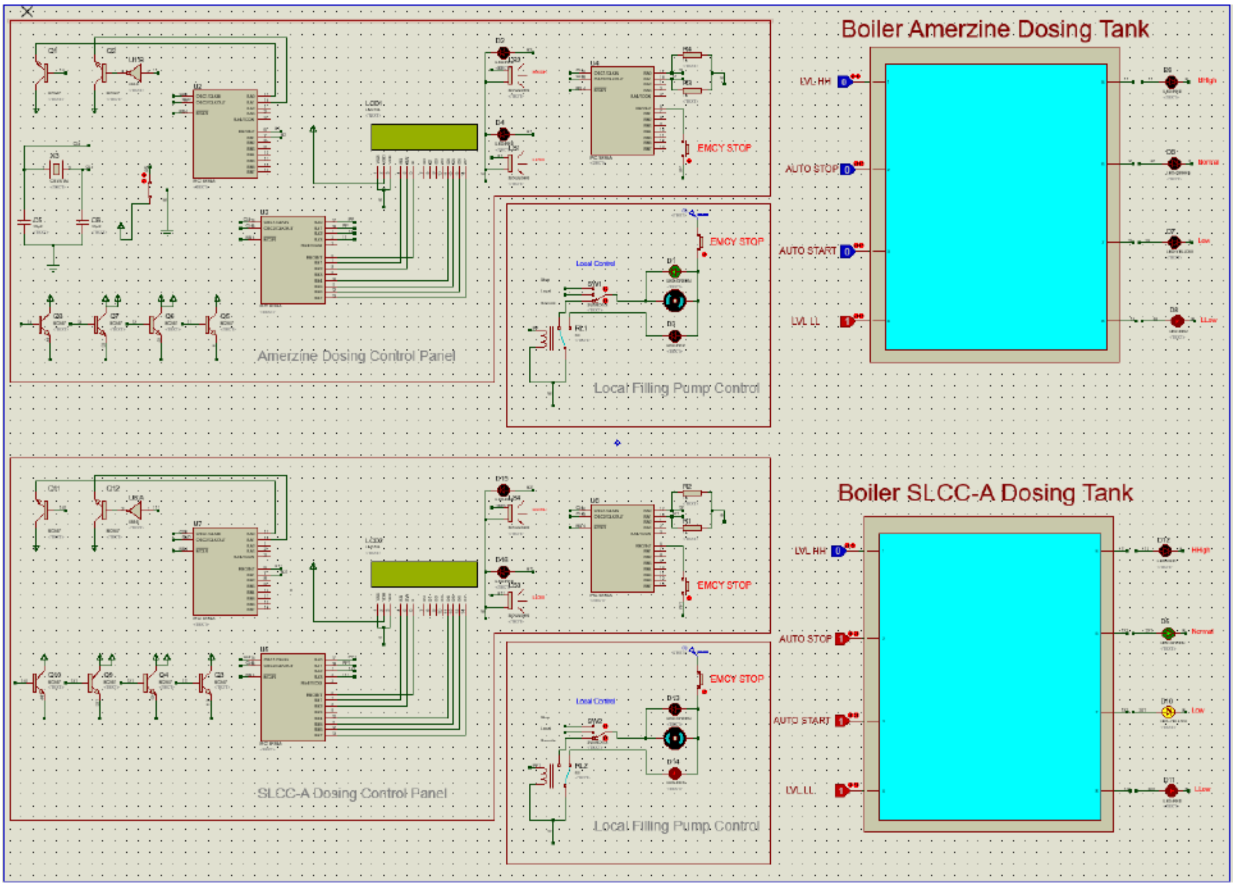

Figure 1 Circuit on Boiler Chemical Dosing Tank

3.3.4 System Architecture Reference

To better understand the layout of the water flow, chemical dosing, and level monitoring involved in this project, a reference to a sewage treatment system is illustrated in Figure 2. While the systems differ in scale and application, the operational concepts of chemical dosing, liquid level control, and pump automation are fundamentally similar.

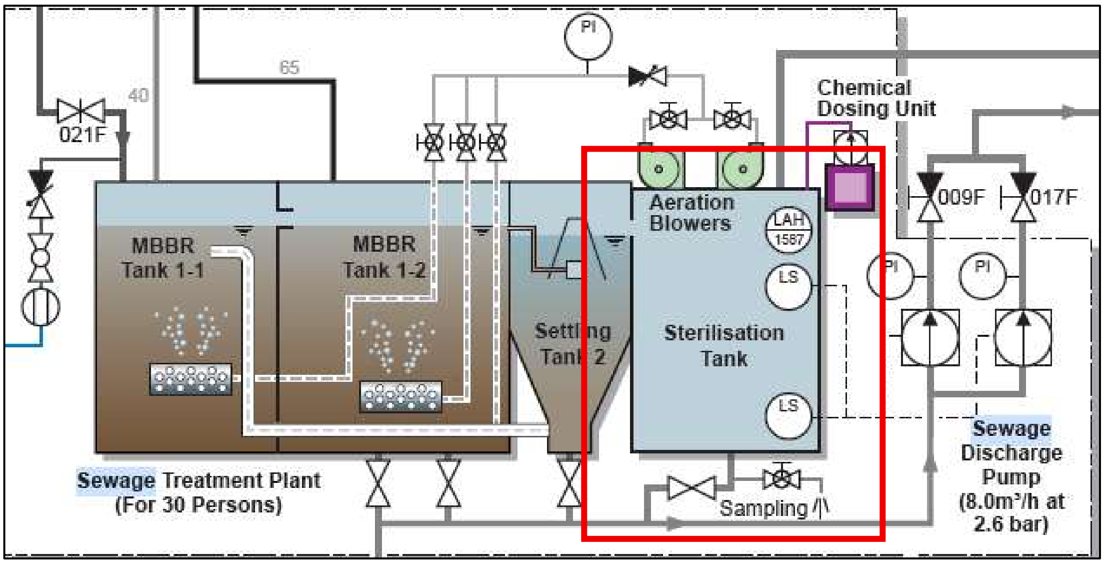

Figure 2 Schematic diagram of a sewage treatment plant showing integration of chemical dosing and discharge systems

The Chemical Dosing Unit shown in the schematic demonstrates where the microcontroller-based automation proposed in this project could be implemented particularly in managing refill cycles and safety cut-offs (Microchip Technology Inc., 2001). The integration of solenoid valves and float-based sensing would align well with the mechanisms shown.

3.3.4 Logic Flow Table

The logic flow table illustrates the operational behavior of the automated distilled water refill system based on input signals from various float sensors. Each float sensor represents a specific water level condition that determines whether the pump is activated or deactivated. The table also defines the corresponding alarm states through LED and buzzer indicators, ensuring both low and high water levels are appropriately monitored. This logical arrangement enables efficient control and protection of the boiler system

Table 1 Truth table of automated distilled water refill system

Low Level Alarm Float	**Start Pump Float**	**Stop Pump Float**	**High Level Alarm float**	**Pump for Distilled Water Filling**	**Low Level Alarm (LED and Buzzer)**	**High Level Alarm (LED and Buzzer)**
1	1	1	1	0 (stop)	0	1
1	1	1	0	0 (stop)	0	0
1	1	0	0	0 (stop)	0	0
1	0	0	0	1 (start)	0	0
0	0	0	0	1 (start)	1	0

3.3.5 Flowchart Description

The flowchart above illustrates the logical decision-making process used by the microcontroller to control the water refilling system based on the input received from the four float sensors (Ding & Shi, 2019).

The system begins by continuously monitoring the float sensor inputs. The decision process starts by checking if the Low-Low Level float (Float 1) is activated, which indicates a critically low water level in the chemical dosing tank. If triggered, a low-level alarm (buzzer and light indicator) is activated immediately.

Next, the system checks whether the Low-Level float (Float 2) is triggered. If yes, it activates the water pump, allowing distilled water to refill the tank. The pump remains active until the High-Level float (Float 3) is triggered, at which point the pump stops automatically to prevent overfilling.

Finally, the system checks if the High-High Level float (Float 4) is triggered. If it is, this indicates that the tank has reached a dangerously high level, and a high-level alarm is activated.
Once all conditions are evaluated, the microcontroller loops back to continue monitoring the float sensors, ensuring real-time automation and system safety.

This logic ensures proper control of the distilled water pump, minimises human intervention, and includes failsafe alarms for both underfill and overfill conditions

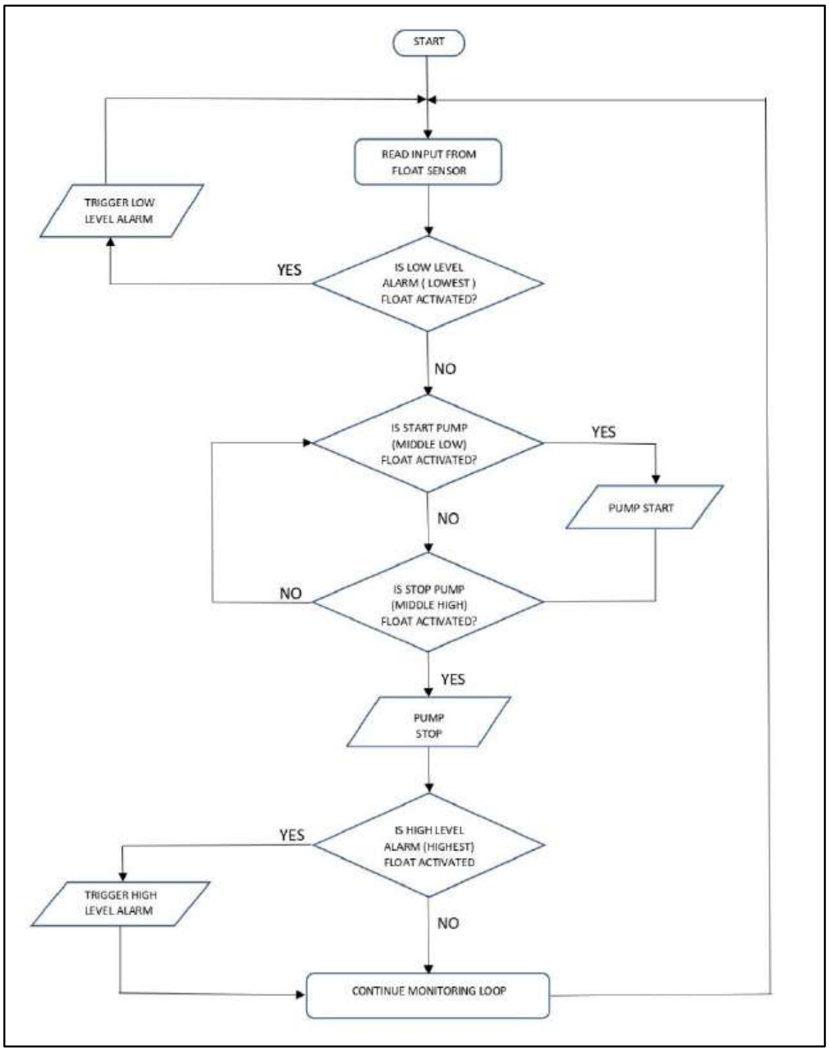

Figure 3 Flow chart diagram of automated distilled water refill system

4.0 RESULTS AND ANALYSIS

The intelligent water refill system for the chemical dosing tank was successfully prototyped and tested under simulated operational conditions. The system demonstrated its capability to automatically regulate distilled water levels using real-time float sensor feedback, thereby ensuring both safety and reliability in the refilling process (Flowline, 2022a; Flowline, 2022b). The integration of microcontroller logic with mechanical float sensors enabled precise control of the distilled water pump operation, thereby fulfilling the primary objectives of the project.

4.1 System Responsiveness and Accuracy

The prototype responded to changes in water levels within an average of 1.5 seconds following the detection of sensor state transitions (McMaster Carr, 2024). Each float switch provided a clean digital signal with no significant bouncing, owing to the implementation of internal debounce logic in the microcontroller code. Pump activation was smooth, with an estimated actuation delay of less than 500 milliseconds from signal detection to pump response.

Water level detection accuracy was evaluated based on float activation thresholds. The system showed consistent behaviour with a variance of ±3 mm in fluid level detection, which is considered acceptable for non-precision dosing tank operations. In simulated low-level conditions, the buzzer alarm was triggered correctly in all 20 test cycles, proving the system's reliability in alerting operators of critical levels.

4.2 System Stability and Operational Robustness

The system underwent 40 continuous test cycles over a 5-hour operational window, simulating various scenarios of water usage and refill. It maintained stable performance throughout, with no observed logic faults or component failures. The microcontroller's ability to interpret float inputs and make real-time decisions based on the truth table logic ensured efficient system behaviour.

The logic prevented simultaneous activation of contradictory states (e.g., alarm and refill at full tank). The refill process automatically ceased upon activation of the top float, effectively preventing overflow. A built-in wait period of 3 seconds was introduced after pump deactivation to reduce potential rapid cycling and mechanical wear.

4.3 Limitations

While the system performed reliably under controlled test conditions, several limitations were identified that may affect performance in real-world applications:

- **Scale and Tank Pressure Constraints**: The testing was performed on a scaled-down acrylic tank. Performance under higher pressure, larger volume tanks, or with actual dosing chemicals may introduce unforeseen challenges such as delayed sensor float response due to fluid viscosity or density.
- **Sensor Mechanical Wear**: The float switches used are mechanical and may degrade over time, especially when exposed to reactive or corrosive chemicals. Regular inspection and replacement intervals must be established for long-term use.
- **Lack of Data Logging**: The current version lacks a data logging function, which would be useful for tracking system history, performance trends, and maintenance needs.

4.4 Proposed Future Enhancements

To address the identified limitations and extend the utility of the system, several future enhancements are recommended:

- **Incorporation of Chemical-Resistant Float Sensors**: Upgrade to industrial-grade sensors designed for chemical immersion to improve lifespan and reliability.
- **Real-Time Monitoring and Remote Control**: Integrate an IoT module (e.g., ESP32) for wireless monitoring, allowing remote control and water level alerts via smartphone or computer interface.
- **Data Logging Capability**: Implement EEPROM or SD card-based storage for recording sensor states, pump activations, and alarm events to support better maintenance planning.
- **Failsafe Redundancy**: Add a secondary microcontroller or watchdog timer to monitor the primary system and activate emergency shutdown procedures in case of failure.
- **Adaptive Control Algorithm**: Replace the basic truth table logic with a more advanced timing or flow-rate-based control system, potentially using PID control for more dynamic adjustment in high-demand environments.

5.0 DISCUSSION AND CONCLUSION

5.1 Discussion

The development of the intelligent water refill system for chemical dosing tanks presents a practical approach to managing fluid levels in a controlled and automated manner. The integration of a microcontroller-based logic circuit and float sensors allows for precise monitoring of water levels within the tank. Compared to manual monitoring or less sophisticated systems, this design reduces human error, improves response time, and minimises the risk of chemical wastage due to overfilling.
During the research phase, the design was inspired by a similar configuration used in the sewage treatment plant onboard marine vessels. However, while the sewage system typically discharges fluids when high-level floats are triggered, this project reverses that principle, using float feedback to control water inflow. This contrast demonstrates the system's adaptability to different industrial needs by reinterpreting similar wiring arrangements for new applications.

A major safety consideration involved the risks associated with chemical spillage from the tank. In the event of an overflow, chemicals such as sodium hydroxide may cause skin irritation or hazardous exposure, particularly in confined spaces or if spilled to lower levels beneath the platform. This system mitigates such risks by ensuring timely deactivation of the water pump at high water levels and triggering an alarm under critical low-level conditions.

In addition, the selection of construction materials for the float sensors and internal piping was crucial. Only chemically compatible materials were chosen to prevent deterioration or unintended chemical reactions. These were matched against compatibility charts and aligned with standards commonly applied in marine hot well systems, albeit resized to suit the tank’s operational volume and dimensions.

The implementation of logic-based control using the PIC16F84A microcontroller and float sensors proved effective. The logic truth table and corresponding flowchart validate the operational sequence through which the system functions, confirming reliable performance under expected conditions. Furthermore, the design was simulated and tested in Proteus prior to physical deployment, which reduced debugging time and enabled validation of sensor input handling. A physical switch was also installed for manual operation of the pump as a contingency measure in the event of automation failure, thereby enhancing overall system reliability.

5.2 Conclusion

The project successfully demonstrates an intelligent, microcontroller-based refill system tailored for chemical dosing tanks. It applies well-understood logic from existing marine sewage systems, adapts it for an inverse operational purpose, and embeds safety, automation, and chemical compatibility into its core design.

By employing a low-cost and programmable microcontroller, together with float sensors and a distilled water pump, this system allows for seamless and safe chemical dilution water management. It ensures that the tank remains filled within safe thresholds while providing timely alerts in case of critical low water levels. The added manual switch further enhances operational flexibility and safety.

The system stands out as a simple yet robust solution that can be scaled or modified for other industrial liquid-level applications. It not only improves operational efficiency but also enhances workplace safety by reducing manual intervention and limiting potential chemical exposure. Future improvements may include the integration of remote monitoring capabilities or additional redundancy layers to further increase system resilience

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the lecturers who, although not directly involved in this project, provided valuable assistance in addressing specific queries. Appreciation is also extended to the engineers who shared brief but helpful insights that contributed to the development of the system.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN: 2590-345 e ISSN: 2976-3843 Volume 6 Issue 1 Year 2025

FRESH WATER GENERATOR SMART CHEMICAL DOSING SYSTEM

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ABSTRACT

Onboard merchant vessels, the efficient utilisation of waste energy is essential, particularly for the generation of freshwater. To achieve this, ships are typically equipped with freshwater generators (distilling plants) that operate using waste heat from engine operations. The main advantage of using onboard distillation systems is the significant reduction in operational costs by minimising dependency on shore-based freshwater supplies, while simultaneously maximising energy recovery from waste heat. This study focuses on the importance of chemical dosing in maintaining the performance and efficiency of the distilling plant. The findings of the research highlight three key factors affecting system efficiency which is reduction in freshwater production caused by improper dosing and system fouling, salt deposit formation (scaling) on the evaporator plates, which hinders heat transfer and reduces efficiency. To mitigate this, the plant must be operated within the optimal temperature range of 35°C to 45°C to minimise the risk of excessive evaporation and foam formation. Lastly, key factor affecting efficiency is lack of operator knowledge and training, which often results in poor maintenance practices and suboptimal chemical dosing, ultimately affecting the long-term performance of the system. The integration of automated chemical dosing systems is recommended to improve operational stability, reduce maintenance costs, and ensure reliable freshwater production onboard.

Keywords: Chemical, Dosing, Efficiency, Microcontroller, Wastewater.

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1.0 INTRODUCTION

In modern maritime operations, the utilisation of renewable energy and the recovery of waste energy have become increasingly common, particularly within the shipping industry. These practices aim to reduce pollution and operational costs, in accordance with the requirements of the International Convention for the Prevention of Marine Pollution (MARPOL) Annex VI, Regulation 22, which mandates that all merchant vessels comply with the Ship Energy Efficiency Management Plan (SEEMP) (International Maritime Organization [IMO], 2025). One widely adopted method involves the use of seawater and thermodynamic principles to generate distillate water for daily crew consumption and equipment use. This process is typically facilitated by a Fresh Water Generator (FWG), which harnesses waste heat from the ship's engine or steam system to evaporate and condense seawater into potable water (Faităr et al., 2021).

To ensure the FWG operates at an optimal level, continuous monitoring of production parameters and system efficiency is essential. Historically, chemical dosing was performed manually to prevent the formation of scale and to inhibit corrosion, both of which may result from the heating of seawater in the evaporator section of the plant (Wang and Zhao, 2022). Manual dosing, however, is subject to human error and often results in inconsistent chemical quantities that do not align with manufacturer

ALAM Journal of Maritime Studies. Volume 6 Issue 1 Year 2025
ISSN: 2590-345 e-ISSN: 2976-3843

specifications. (Insani Ilham et al., 2022). Over time, scaling on evaporator plates reduces heat transfer efficiency, resulting in a noticeable decline in plant performance (Ahmed and Mohamed, 2024). An automated chemical dosing system can significantly mitigate these inefficiencies while enhancing system reliability and safety. (Bello & Owoeye, 2022; Wang & Gu, 2022).

1.1 Dosing Chemical Operation

During plant operation, a vacuum is created in the evaporator chamber. A dedicated dosing tank, fitted with a flow control valve, automatically injects a precise quantity of chemical into the system via the seawater feed line (Cazarez-Candia and Ortega-Delgado, 2021). This controlled dosing ensures that the correct concentration of chemicals enters the shell side of the evaporator, thereby promoting consistent protection against scaling and corrosion (NSF International, 2024; Marine Chemicals Inc., 2024). Figure 1 illustrates the location of the dosing point within the FWG system.

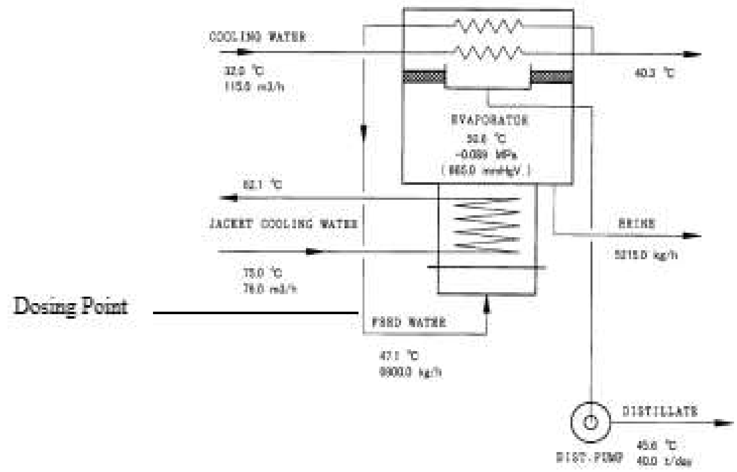

Fig 1 Chemical dosing point in Fresh Water Generator

1.2 Dosing Chemical Type

The chemicals used in the dosing process must possess specific properties, including:

- Antiscalant agents to prevent salt scaling on heat transfer surfaces (Ahmed & Mohamed, 2024).
- Corrosion inhibitors to protect metal components from chemical and electrochemical degradation (Wang & Zhao, 2022).
- Biocides to eliminate microbial growth and biofouling that could affect water quality and system cleanliness (Liu et al., 2024).

Appropriate chemical selection is essential for maintaining both equipment longevity and water purity, particularly in marine environments where operational reliability and regulatory compliance are critical. (NSF International, 2024; Vizag Chemical International, 2024).

2.0 LITERATURE REVIEW

Human factors play a vital role in ensuring the operational efficiency and safety of a Fresh Water Generator (FWG) system. In many marine and industrial settings, the FWG is responsible for converting seawater into potable water, which is subsequently used for both consumption and machinery operations

(Faităr et al., 2021). To achieve reliable and consistent water quality, precise chemical dosing is essential. Inaccuracies arising from manual handling can lead to several operational issues, including water contamination, equipment failure, and increased operational costs (Mohamed et al., 2023). To reduce dependence on manual intervention and minimise the risk of human error, the development of an automated dosing and filling control system is essential (Bello and Owoeye, 2022; Wang and Gu, 2022; Luo et al., 2022). The system implemented in this project addresses common errors through sensor-based automation and programmed logic (Cazarez-Candia and Ortega-Delgado, 2021). Key areas of concern include:

2.1 Overdosing of Chemicals

In the FWG system, overdosing of treatment chemicals, such as antiscalants or chlorination agents, may result in chemical contamination of the produced water. This not only renders the water unsafe for human consumption but may also cause damage to downstream equipment, particularly heat exchangers, pipelines, and boilers, where chemical buildup can lead to corrosion or thermal inefficiency (Ahmed & Mohamed, 2024; Wang & Zhao, 2022).

2.2 Underdosing of Chemicals

Insufficient chemical dosing results in scaling and corrosion within the FWG system. Without adequate chemical treatment, minerals and impurities present in seawater can deposit on heat transfer surfaces, reducing efficiency and increasing energy consumption (Mohamed et al., 2023; NSF International, 2024). Over time, this can result in equipment damage, performance degradation, and unplanned maintenance shutdowns (Faităr et al., 2021).

2.3 Resource Wastage

Manual errors, such as failing to stop the chemical dosing pump in a timely manner or overlooking tank levels, may result in overflow of the dosing tank, chemical wastage, or unnecessary system wear (Insani Ilham et al., 2022). These incidents not only waste resources but also increase the operational cost of running the FWG system and pose a risk of environmental non-compliance in maritime operations. (IMO, 2025.; Liu et al., 2024).

3.0 PROCEDURES

This research project integrates both practical experimentation and case study methodology to ensure that the designed automation system operates reliably and as intended. The core objective of the system is to automate the filling and chemical dosing processes in a Fresh Water Generator (FWG) dosing tank, using water level sensors, microcontroller logic, and simulated components.

Simulations were conducted using the Proteus Design Suite, while embedded control logic was programmed using the CCS C Compiler. Together, these tools validate the functionality of the water level sensors and the automatic operation of both the freshwater and chemical dosing pumps. The simulation replicates real-world behaviour by testing the system’s response to varying water level conditions.

Auto Filling Process Flow

Figure 2 below shows complete flowchart of the automation process FWG dosing tank system. The system logic is based on three sensor points, each corresponding to specific tank levels and system actions:

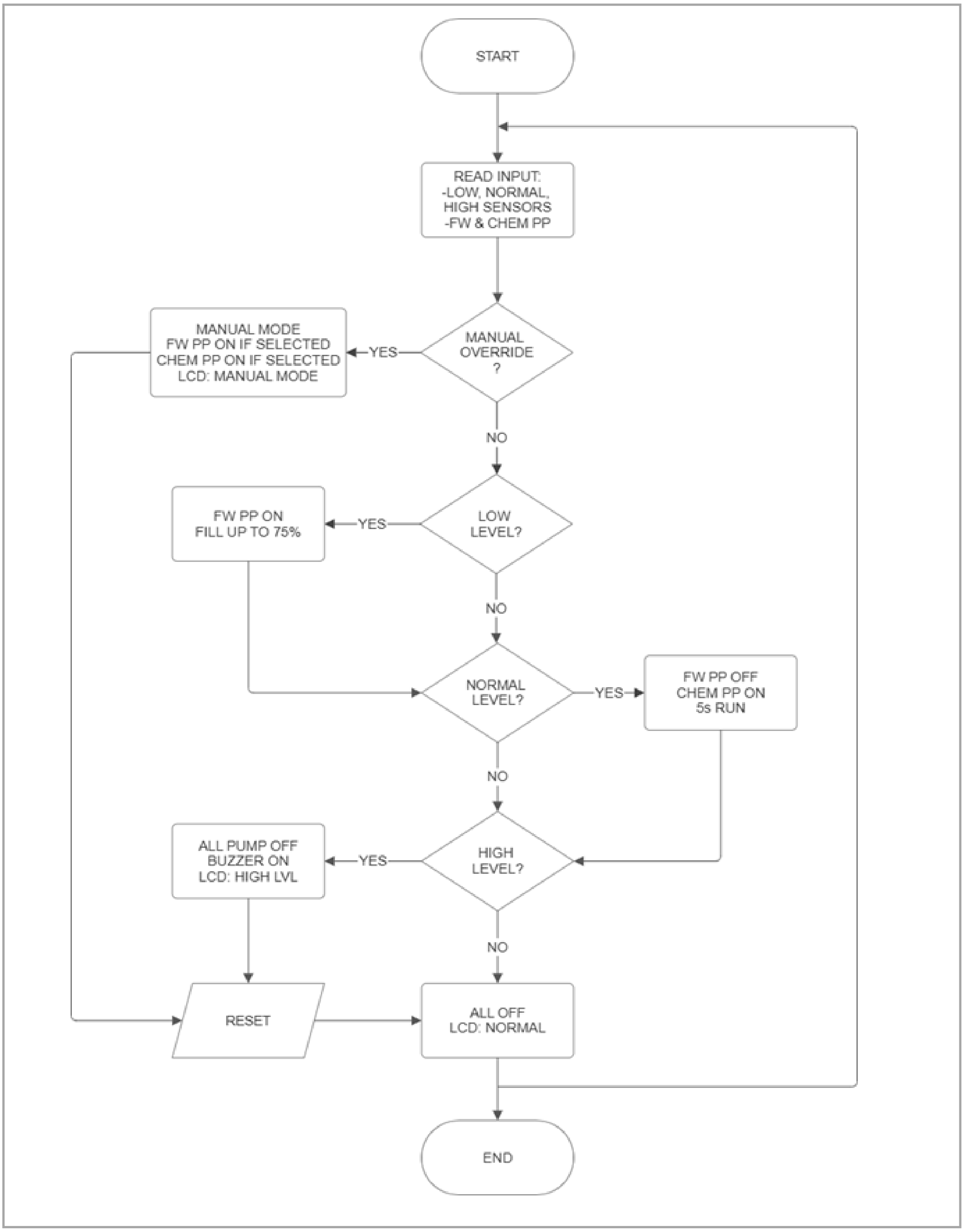

Fig. 2. Fresh Water Generator (FWG) Dosing Tank Auto Filling Process Diagram

ALAM Journal of Maritime Studies. Volume 6 Issue 1 Year 2025
ISSN: 2590-345 e-ISSN: 2976-3843

Table 1. Truth table shows how sensor input values correspond to specific system responses.

Operation Mode	Low Level	Normal Level	High Level	Manual FW Pump	Manual Chemical Pump
FW pump running	1	0	0	1	0
Chemical pump running	0	1	0	0	1
Buzzer On	0	0	1	0	0

Table 1 shows the relationship between the sensor input levels and the system responses of the Fresh Water Generator (FWG) auto-filling system. At low level, the freshwater pump starts to fill the tank. When the normal level is reached, the chemical pump operates for dosing. At high level, both pumps stop and the buzzer activates to indicate a full tank. Manual override buttons allow independent pump control when required.

Figure 3 shows the simulation which accurately mimics real-world behaviour and validates the program logic. By observing how each sensor input affects the outputs (pumps and buzzer), the system's responsiveness and correctness can be evaluated.

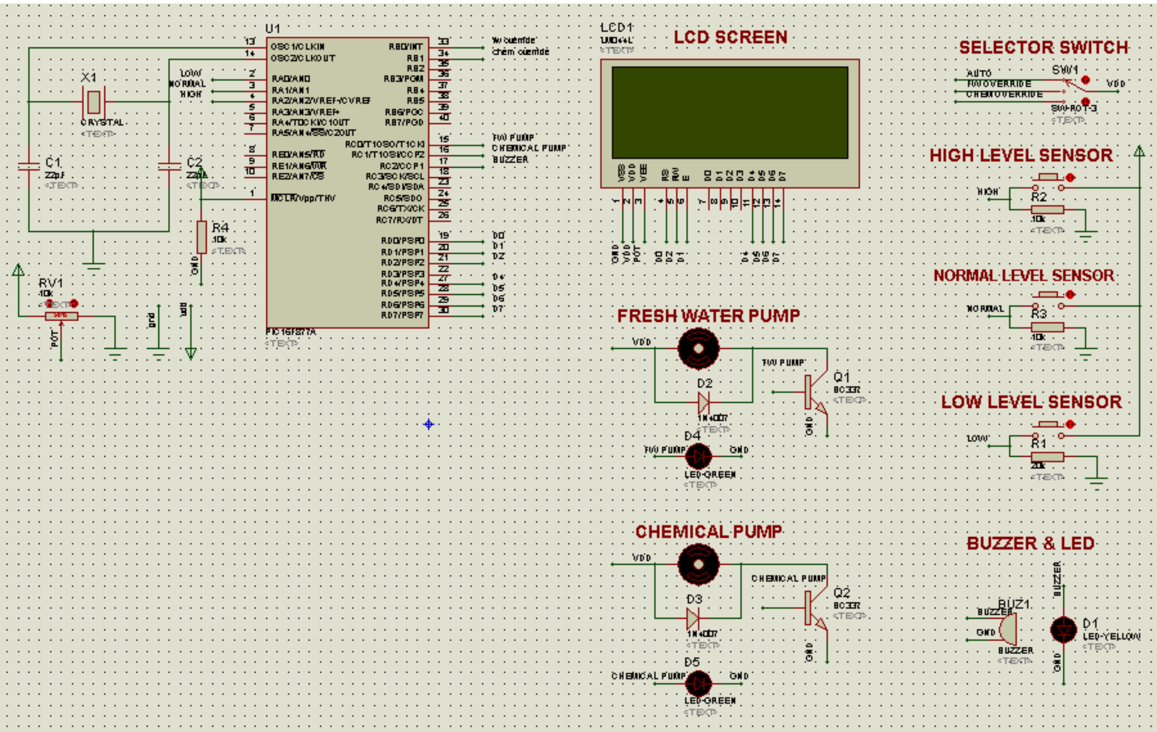

Fig. 3. Displays the Proteus environment used to simulate the system.

4.0 RESULTS

With the integration of a microcontroller and a well-structured control algorithm, the performance of the Fresh Water Generator (FWG) can be significantly enhanced. The automated system ensures accurate chemical dosing, thereby eliminating the risks of underdosing and overdosing, both of which may compromise water quality and system efficiency. By maintaining the correct chemical concentration, the plant is able to produce higher quality distilled water, suitable for both domestic and operational use onboard.

Furthermore, the implementation of an automated start-stop sequence improves the overall resource efficiency of the system. It optimises the use of water, chemicals, and manpower, reduces wastage, and enhances operational safety. This automation not only lowers the likelihood of human error but also contributes to reduced maintenance costs and improved reliability of the freshwater generation process.

- First Sensor (10% level - LOW):
  - When the water level drops to this point, the system automatically activates the freshwater pump to begin filling the tank.
  - A message is displayed on the LCD indicating the pump is running and the tank is being filled as shown in Figure 4.
  - This condition represents the "low-level trigger".

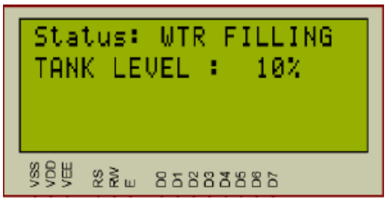

Fig. 4. LCD Display Output During Fresh Water Filling Up

- Second Sensor (75% level - NORMAL):
  - When the tank reaches this level, the system automatically stops the freshwater pump and initiates the chemical dosing pump.
  - The LCD updates the status to "Chemical Dosing in Progress" as shown in Figure 5.
  - The chemical dosing pump operates for a predefined time (e.g., 5 seconds) using a countdown display to simulate precise chemical injection.

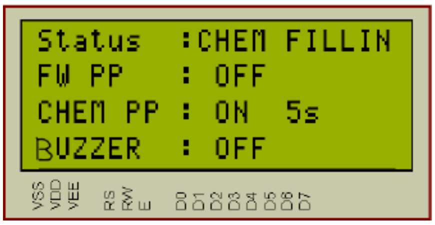

Fig. 5. LCD Display Output During Chemical Filling Up

- Third Sensor (100% level - HIGH):
  - This is the final sensor point located at the top of the dosing tank.
  - When triggered, the system automatically stops the chemical and freshwater pump if running and activates the buzzer, serving as an overfill protection and safety alert.
  - This state overrides all other inputs, ensuring that both pumps are turned off and the system enters a lock-safe mode. The LCD will display as shown in Figure 6.

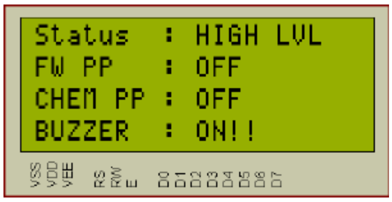

Fig. 6. LCD Display Output During High Level

Simulation Setup and Functionality

The system components were modelled as follows:

- Microcontroller: PIC16F877A simulates all logical operations and controls the peripherals.
- Toggle Switches: Used to manually represent the sensor states (LOW, NORMAL, HIGH), allowing users to simulate different tank levels.
- DC Motors / LEDs: Represent the Fresh Water Pump and Chemical Dosing Pump respectively. Their ON/OFF states show pump activity.
- Buzzer (Sounder): Indicates high-level alarm.
- LCD Display (LM044L): Provides real-time system status feedback, such as pump states, tank level percentage, and warning alerts.

Each simulated level condition (10%, 75%, 100%) is manually selected using toggle switches, enabling clear observation of how the system transitions through each mode – auto freshwater fill, chemical dosing, and alarm state.

Figure 7 shows the LCD screen display when FWG dosing system is on NORMAL condition. This is due to water level is at normal level without triggering any float switch.

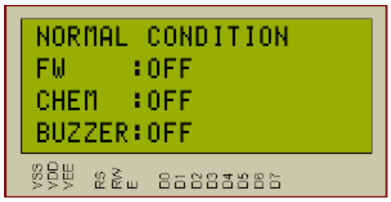

Fig. 7. LCD Display Output During Normal Condition

Figure 8 shows the LCD screen display when freshwater pump is selected to run in manual mode. This option will allow the user to manually fill the dosing tank with freshwater for other purpose such as rinsing the dosing tank with freshwater.

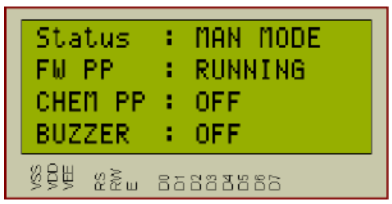

Fig. 8. LCD Display Output During FW pump manual mode

Figure 9 shows the LCD screen display when chemical pump is selected to run in manual mode. This option will allow the user to manually top up the chemical due to minor adjustment of amount of chemical needed if required by the maker.

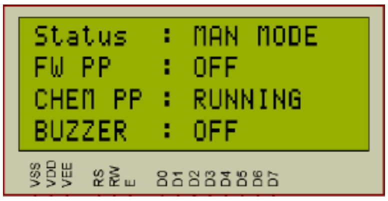

Fig. 9. LCD Display Output During Chemical pump manual mode

5.0 CONCLUSION

The presence of appropriate chemical dosing within the system plays a crucial role in enhancing the overall performance and reliability of the Fresh Water Generator (FWG) plant. Accurate dosing contributes to improved operational efficiency, optimised maintenance schedules, and extended equipment lifespan. In contrast, traditional manual dosing methods are often slow, inconsistent, and susceptible to human error, which may result in system inefficiencies and unplanned maintenance.

Modern automation technologies offer significant advantages through real-time control, precise dosing, and reliable feedback mechanisms. Advanced technologies, such as fibre-optic and microwave-based sensors, are being explored for integration into detection and control systems to further enhance accuracy and responsiveness. These innovations help reduce maintenance costs, prevent unexpected equipment failures, and optimise chemical usage.

The automated chemical dosing system implemented in this project represents a progressive step towards improving the production rate and performance of the FWG. Continued research and development in this area are essential to achieving greater robustness and efficiency across various industrial applications, particularly within the maritime sector.

In conclusion, this project underscores the potential of automation in addressing the limitations of traditional chemical dosing methods. The findings support the adoption of modern control systems to ensure sustainable, safe, and efficient operations. Future studies may focus on expanding system capabilities, refining sensor technologies, and integrating machine learning for predictive maintenance and adaptive control.

ACKNOWLEDGEMENTS

The project team members would like to thank Akademi Laut Malaysia Melaka for their acknowledgment and their support on study materials and guideline during completing this project.

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ALAM JOURNAL OF MARITIME STUDIES

ISSN : 2590-345 e ISSN : 2976-3843 Volume 6 Issue 1 Year 2025

Generator Sump Level Monitoring and Automatic Control System with Alarm Features

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Abstract - A generator sump tank is a reservoir that stores lubricating oil for the generator's engine. It serves as a holding space for the oil and facilitates its circulation throughout the engine for lubrication. In most designs, the sump is integrated into the engine's crankcase. Manual monitoring is often unreliable and may result in overflow, pump damage, or dry running. This project introduces a microcontroller-based system to automate sump tank monitoring, pump control, and alarm management using level sensor switches and buzzers. The tank is equipped with a level indicator for local monitoring, along with a dipstick and sensor switches that function as control elements. These sensor switches transmit signals to automatically start and stop the pump. Additionally, they provide input to the monitoring and alarm system, enabling status indications for pump operation and triggering alarms for low-low and high-high oil level conditions. The developed system achieved 100% accuracy in pump control and alarm activation throughout the testing phase, demonstrating high reliability and operational consistency.

Keywords: Automatic Pump Operation, Generator Sump Tank, Level Sensor Alarms, Microcontroller-Based Automation, Oil Level Alarm System

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1.0 INTRODUCTION

In maritime operations, the reliability of generator systems is vital to ensuring a continuous power supply during voyages. A sump tank within a generator, stores lubricating oil which is essential for minimising friction, reducing wear, and extending the operational life of the engine. However, manual monitoring of sump oil levels has proven unreliable due to human error and delays in corrective action. Improper monitoring may lead to sump overflow, pump failure, or oil starvation of the engine, compromising vessel safety and operational performance. This study aims to design and implement an intelligent generator sump level monitoring system, equipped with automated pump control and alarm capabilities. The integration of sensor technology with microcontroller-based automation ensures effective monitoring, real-time alerts, and immediate corrective action without the need for constant human intervention.

2.0 RESEARCH CONTEXT

Recent research in marine automation increasingly focuses on smart monitoring systems to enhance operational reliability, safety, and environmental compliance. Alqadami et al. (2020) emphasise that integrating sensor-based monitoring with automated decision-making can significantly reduce mechanical failures and operational risks in marine engineering systems. Similarly, Chen et al. (2022) demonstrate that the use of smart sensors in pump monitoring improves predictive maintenance accuracy, thereby reducing downtime and extending equipment lifespan.

Traditional sump level monitoring in ships typically involves manual oil inspections using dipsticks or visual gauges. While cost-effective, this approach is time-consuming, prone to human error, and often lacks real-time responsiveness (Sharma, 2020). The transition to microcontroller-based monitoring addresses these limitations by enabling continuous data acquisition, processing, and automated control. (Che Kar et al., 2022).

Recent developments in Internet of Things (IoT) integration, as demonstrated by Mat Hussain et al. (2025), enable microcontrollers to process signals from multiple level sensors, display readings in real time, and trigger alarms for abnormal conditions. These advancements align with the International Maritime Organization (IMO) objectives on energy efficiency and safety, as outlined in the Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2021). Furthermore, predictive maintenance supported by data analytics (Latrach, 2023; Hashemipour & Singh, 2025) ensures proactive intervention before critical failures occur, thereby reducing both maintenance costs and environmental impact.

3.0 PROCEDURES

The proposed microcontroller-based sump tank monitoring and control system is designed to automate lubrication oil level management for shipboard generators. The design draws inspiration from industrial pump automation systems (Chen, Zhang, & Li, 2024; Community Project, 2022) and is optimised for marine environments, where equipment reliability and safety are paramount.

3.1 Procedure Relevance

This methodology aligns with contemporary automation design principles in marine engineering, combining sensor networks, microcontroller-based control, and predictive maintenance frameworks. It leverages proven approaches from industrial IoT monitoring (MDPI Authors, 2024; Allahloh et al., 2023), tailoring them to the operational requirements of shipboard sump lubrication systems.

The system consists of the following units:

1. Sump Tank Unit: Equipped with four level switch sensors and a level indicator (High-High Alarm, Auto Stop, Auto Start, and Low-Low Alarm), along with transistors.
2. Transfer Pump Unit: Includes a relay, pump, power supply for the pump, 3-way switches (Remote, Local Start, Local Stop), and an Emergency Stop Push Button.
3. Pump Control Unit: Utilises a PIC16F84A Microcontroller, crystal, capacitor, power supply with switch, resistor, and an Emergency Stop Push Button.
4. Monitoring & Alarm System: Incorporates a PIC16F84A Microcontroller, crystal, capacitor, transistor, power supply with switch, 16x2 LED display, buzzer, and LED alarm indicators.

The system can operate in either automatic or manual mode. Under normal conditions, it primarily operates in automatic mode (Djalilov et al., 2022; IJERT, 2024). In this mode, two level switches control the pump's operation:

- When the oil level drops, the pump remains inactive.
- Once the Auto Start level sensor is deactivated, the pump begins operating until the Auto Stop level is reached, at which point it automatically shuts down.

In manual mode, the user can directly start or stop the pump at any desired oil level. Monitoring may be performed using the level indicator or, traditionally, with a dipstick.

The system is equipped with two alarms: High-High (HH) Alarm(IMO, 2021; Smart Genset Control, 2025) and Low-Low (LL) Alarm (Hashemipour & Singh, 2025).

- The LL Alarm is typically triggered if the pump is running in manual mode without monitoring, if the Auto Start sensor is defective, or in the event of a major oil leak. It protects the generator from oil starvation, which can cause excessive friction, overheating, and potentially catastrophic engine failure. It also provides an early warning for the operator to take corrective action, such as topping up oil or checking for leaks, before the pump runs dry.

- The HH Alarm is generally triggered if the pump is operated in manual mode without monitoring, if the Auto Stop sensor fails, or in the event of a heavy or continuous fuel leak into the lubrication system. This alarm serves as an early detection mechanism to help reduce fuel wastage in line with the Ship Energy Efficiency Management Plan (SEEMP), as per the International Maritime Organization (IMO). In addition, it prevents overflow that could result in oil spillage, fire hazards, and environmental pollution. The HH Alarm also also protects the pump from overpressure or flooding, thereby reducing the risk of mechanical damage.

In compliance with maritime safety guidelines (IMO, 2021), the system is equipped with two emergency stop push buttons, located at both the local control side and the remote-control side for safety purposes. The figures and table below provide a clearer understanding.

Figure 1. The flowchart illustrates the operational logic of the automatic generator sump monitoring system, including process flow and response actions. The system ensures that the pump operates efficiently, preventing overflow or dry running while maintaining safe sump levels.

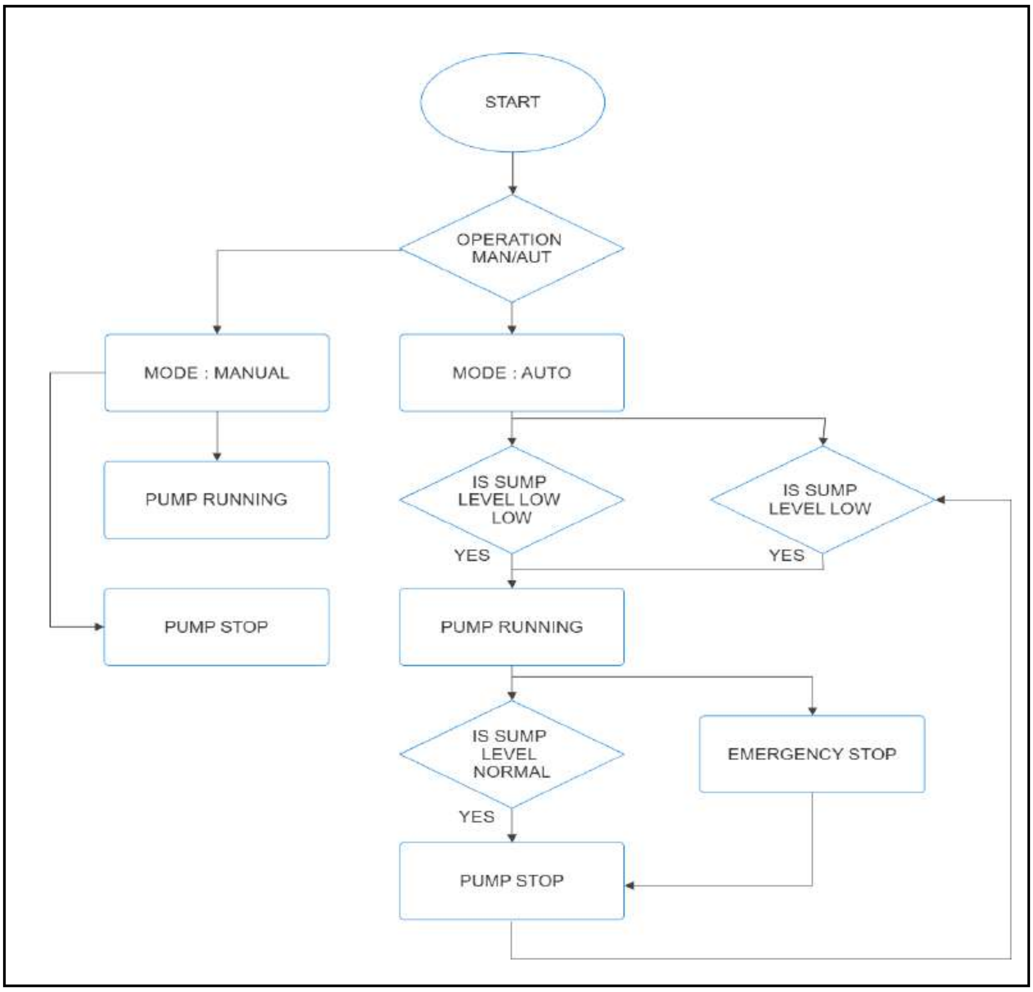

Figure 1. Generator Sump Monitoring Process Diagram

ISSN: 2590-345 e-ISSN: 2976-3843

Table 1. Shows the control logic matrix for a pump automation system based on different alarm and operational conditions, namely High-High (HH) Alarm, Auto Stop, Auto Start, and Low-Low (LL) Alarm. The table summarises the system responses for three main components: Pump, Display, and Buzzer.

Action	HH Alarm	Auto Stop	Auto Start	LL Alarm
Pump	0	0	1	1
Display	1	1	1	1
Buzzer	1	0	0	1

Figure 2. illustrates the automatic sump tank monitoring and control system circuit, which integrates multiple subsystems namely the sensor switch unit, monitoring and alarm system, level indicator, control unit, and transfer pump. This setup is designed to automatically control pump operation based on sump levels, while providing visual and audible alarms for abnormal conditions.

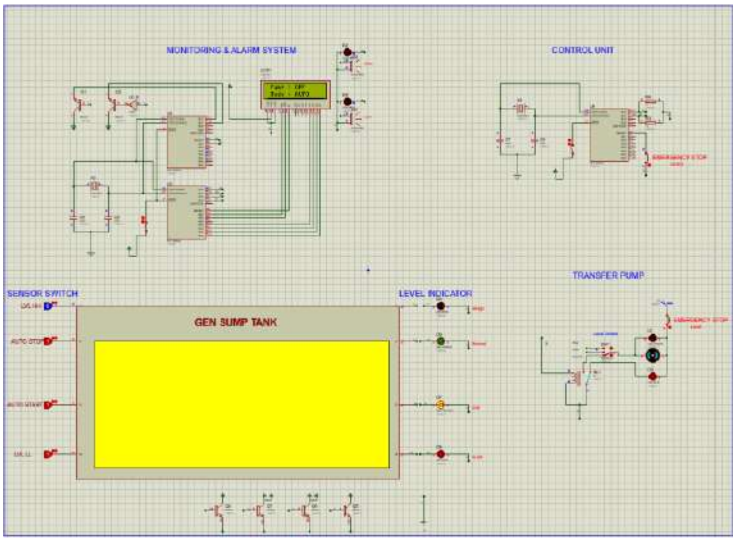

Figure 2. Generator Sump Monitoring Process Diagram

Figure 3. Shows the Tank unit and components such as four level switch sensors, level indicator (High-High Alarm, Auto Stop, Auto Start, Low-Low Alarm), and transistors.

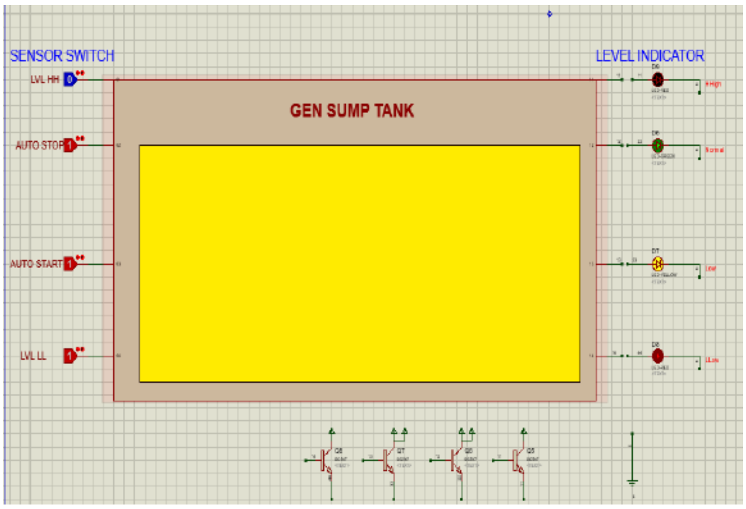

Figure 3. Tank Unit

ISSN: 2590-345 e-ISSN: 2976-3843

Figure 4. Shows the Transfer Pump Unit and Components such as relay, pump, pump power supply, 3-way switches (Remote, Local Start, Local Stop), and an Emergency Stop Push Button.

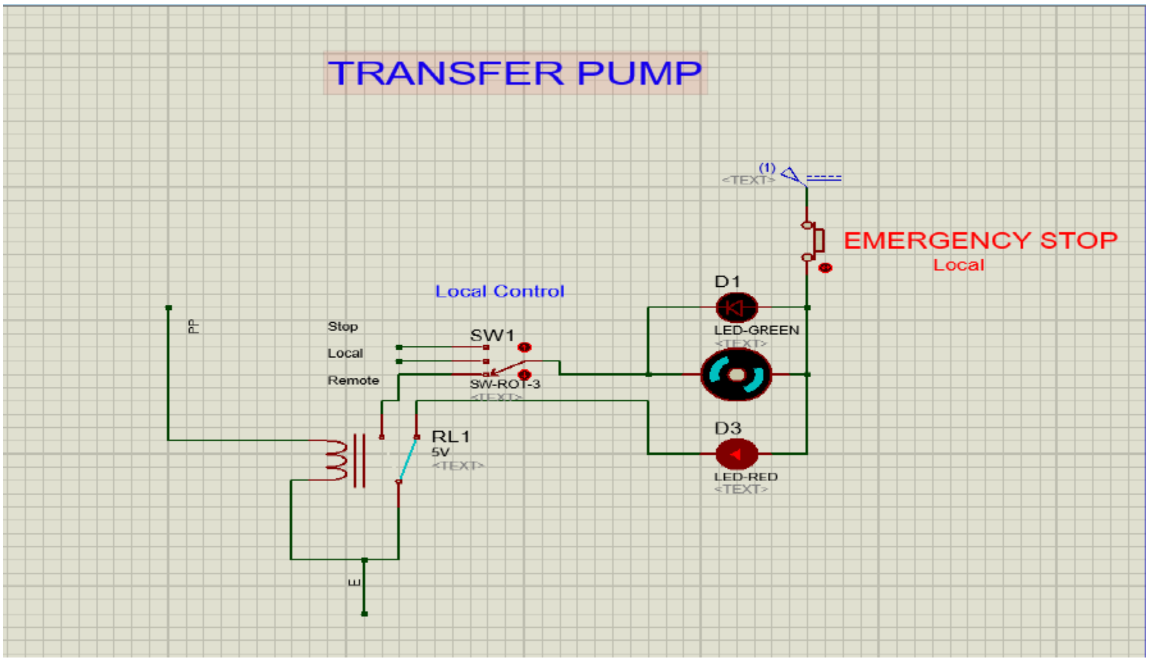

Figure 4. Transfer Pp Unit

Figure 5. Shows the Pump Control Unit and Components: PIC16F84A microcontroller, crystal, capacitor,

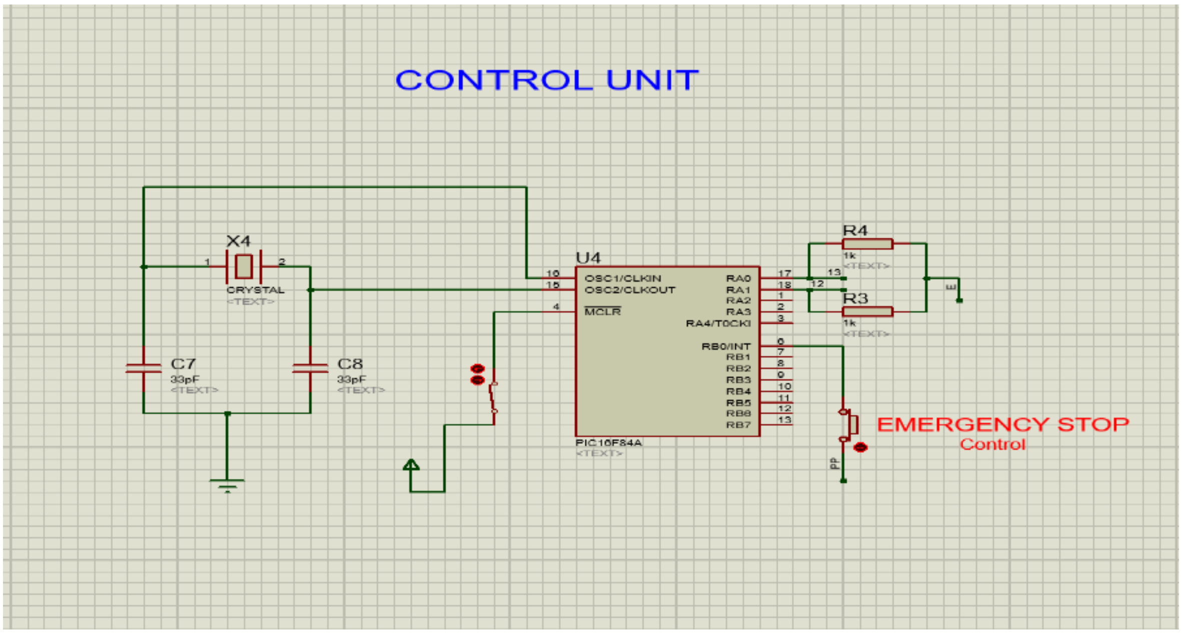

Figure 5. Pump Control Unit

Figure 6. Shows the Monitoring & Alarm System with following components: PIC16F84A microcontroller, crystal, capacitor, transistor, power supply with switch, 16x2 LED display, buzzer, and LED indicators.

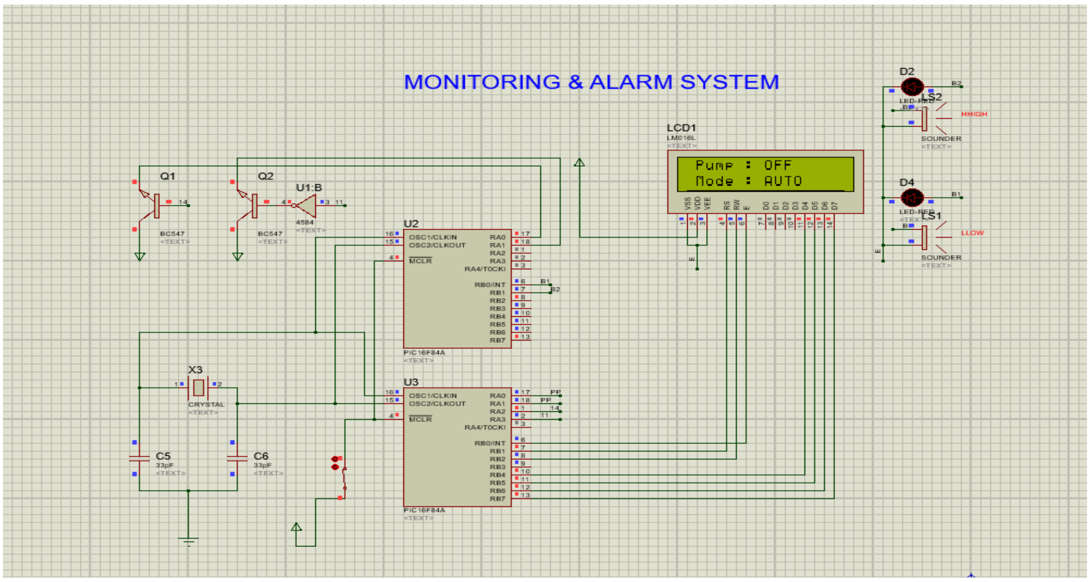

Figure 6. Monitoring & Alarm System

4.0 RESULTS AND ANALYSIS

The intelligent generator sump level monitoring and auto-control system was tested under simulated operating conditions in a controlled laboratory environment. The evaluation focused on the accuracy of level detection, pump responsiveness, alarm functionality, and overall system reliability.

4.1 Automatic Mode Performance

Automatic operation yielded consistent and timely responses to oil level changes. When the oil level dropped below the designated Auto Start point, the pump activated within one second and continued operating until the Auto Stop level was reached, at which point it shut off automatically. This ensured optimal sump oil levels without human intervention.

4.2 Manual Mode Performance

In manual mode, the pump was operated using the manual start switch. The level indicator provided real-time visual monitoring, while the dipstick served as a reliable backup method. Operators were able to successfully start and stop the pump as required, without system errors.

4.3 Alarm System Functionality

The HH and LL alarms were tested under fault and abnormal conditions:

- Low-Low (LL) Alarm: Triggered reliably when oil levels reached critically low points. This provided early warning of possible oil starvation and allowed operators to intervene before damage occurred.

- High-High (HH) Alarm: Successfully activated when oil exceeded the safe limit, preventing overflow and potential oil spillage. In both cases, the buzzer and LED indicators provided clear audible and visual alerts, ensuring operators were promptly informed.

4.4 Safety Features

The dual emergency stop push buttons, installed at the local and control panels, functioned effectively during testing. Immediate shutdown was achieved upon activation, confirming the system's compliance with safety standards.

4.5 System Reliability

Over the course of 50 operational test cycles, the system achieved 100% accuracy in pump control and alarm triggering. No false alarms or operational delays were observed.

5.0 DISCUSSION AND CONCLUSION

The intelligent generator sump level monitoring and auto-control system has demonstrated high effectiveness in ensuring safe and reliable oil management. By integrating microcontroller-based automation with level sensors and alarms, the system successfully reduces reliance on manual monitoring, which is often prone to error. The automatic mode ensures precise control of oil levels, while the manual mode provides flexibility for operators when required.

The inclusion of High-High (HH) and Low-Low (LL) Alarms is a critical feature, as it protects the generator from two major risks: oil starvation and overflow. These alarms, combined with visual and audible indicators, provide early warnings and enhance the overall safety of generator operations. The emergency stop push buttons further reinforce safety, allowing immediate system shutdown during abnormal conditions.

Overall, the system improves operational efficiency, reduces the risk of mechanical failure, and strengthens safety standards in maritime generator operations. Future enhancements could include the integration of wireless communication for remote monitoring, as well as data logging for predictive maintenance and performance tracking.

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