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# 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).

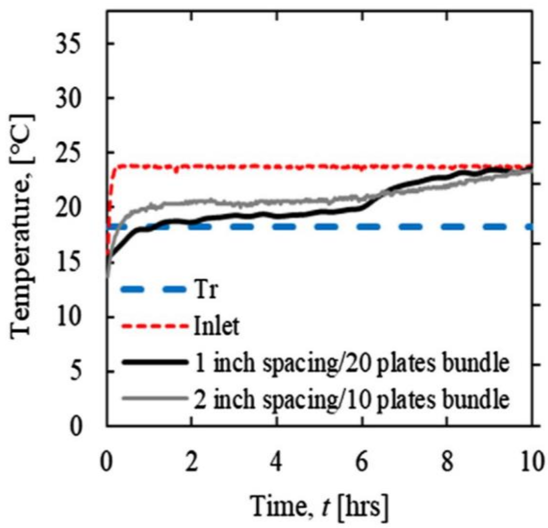
The main objective of the experiment was to thoroughly assess the thermal efficiency of this innovative LHTES system. The researchers performed charging and discharging experiments at different flow rates, while keeping the charging water temperature at 75 °C and the discharging temperature at 25 °C. 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).

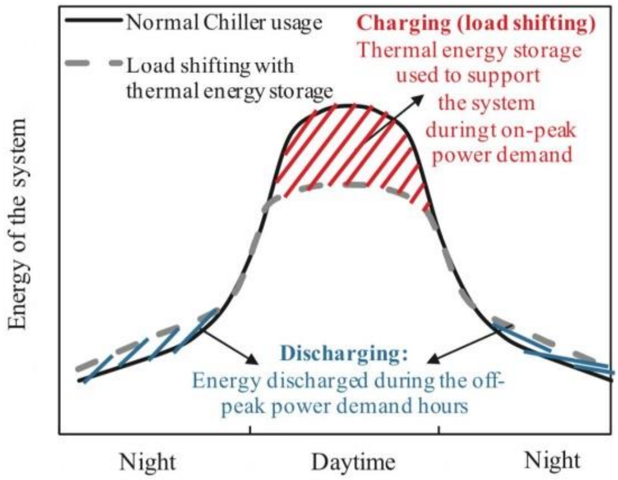
The study also examined the UA value, which quantifies the system's overall heat transmission efficiency. Throughout the range of experiments, the UA value fluctuated between approximately 25 W/k and 70 W/k at flow rates ranging from 100 L/h to 500 L/h. Notably, the UA value showed a small rise while 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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