Comprehensive review of heat exchanger technology for marine heat pumps: geometries, performance, and challenges

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Abstract. Marine heat pumps are a renewable solution for heating and cooling that harnesses the thermal energy stored in seawater. This study provides a review of recent advances in heat pumps, covering five main configurations: double-tube helical heat exchangers, nanofluid-based heat exchangers, staggered tube bundle heat exchangers, capillary coils and plate heat exchangers, whilst examining the three dimensions of system performance: energy, environmental and economic. However, the marine environment poses major challenges that cause operational issues and limit the performance of marine heat pumps, such as fluctuations in seawater temperature, biofouling, corrosion, high salinity and thermal pollution. These challenges directly affect the performance of heat exchangers in marine heat pumps by accelerating material degradation and causing thermal resistance. To resolve these issues, efforts must be made to develop corrosion-resistant materials and heat exchangers with optimized configurations that enhance heat transfer and reduce pressure drops, as well as to utilize efficient fluids such as nanofluids at specified concentrations. The results highlight the need for innovative solutions to ensure the smooth operation of high-performance systems that address all three dimensions by effectively tackling these hostile challenges.

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1 Introduction

Global CO2 emissions from fuel combustion augmented by 1.3% in 2022, attainment pre-COVID-19 grade. Universally, fossil fuels yet consider for 81% of total energy supply, with oil, coal, and natural gas which are considered for global emissions from fuel combustion. Collectively, China, the United States, the EU, India, the Russian Federation, and Japan numbered for global emissions from fuel combustion. Mitigating climate change and decreasing atmospheric greenhouse gas emissions are the aims of the Kyoto Protocol. Many nations have engaged in recent years to turn carbon neutral, with a purpose as early 2060 for China [1].
These pledges underline how immediate it is to diminish greenhouse gas emissions internationally, specifically from industrial funding like heating processes that provide considerably to emissions. The proportion of fossil fuels in universal energy mix has declined steadily over the last ten years with 2% from 2013 to 2023 while energy demand has increased by 15%. Since 2013, renewable energies have augmented by 3% per year, while nuclear has reduced by around 0.5 percentage points per year. This rapid growth makes the transition away from conventional fuels much more difficult than in developed countries.
The global trajectory projected in the stated policy scenario (STEPS) anticipates a peak in consumption of the three main fossil fuels before 2030, with the accelerated deployment of renewable energies, particularly wind and solar photovoltaic (PV) energy, with clean energy growth expected to exceed overall global energy demand growth by the mid-2030s. Achieving these ambitious decarbonization goals requires finding innovative and highly scalable alternatives to conventional fossil fuel-based heating [2].
Marine heat pump (MHP) systems offer a compelling and highly efficient solution by harnessing the stable thermal energy of seawater, which is an essential pathway to reducing dependence on combustion for district heating. However, the long-term successful implementation and sustainability of MHPs are fundamentally linked to resolving the major technical challenges inherent in the marine environment, particularly those that impact the core component of the system: heat exchanger technology.

2 Marine Heat Pumps

Heat pump technology has a major role in economic, environmental, and energy benefits. Heat pumps are more efficient technology for heating and cooling. The International Energy Agency (IEA) names the heat pumps knowledge center a « technology collaboration program on heat pumping technologies» [3].
A heat pump transfers heat using mechanical work from a cold to a hot source. The refrigerant is the transferring fluid used in the first machines to produce cooling. Evaporating the cold source and, condensing the hot source helps to transfer latent heat from the fluid. Heat pumps are employed in diverse fields: heating domestic hot water, cooling, desalination of seawater, etc. The goal is to transfer more energy and consume less mechanical work [4].
A seawater heat pump helps to satisfy the thermal energy demands of a system, generally a residential area or an activity zone, with the availability of marine thermal energy. Its operating principle is similar to that of a refrigerator by extracting energy from the sea and releasing this energy into an external heat exchanger at the back of the refrigerator. These heat pumps produce water at different temperature regimes depending on the application: 15°C/20°C for cooling and hot water at 50°C/45°C for domestic hot water [5].

3 Types of Marine Heat Pumps

Seawater heat pumps (SWHPs) can be classified into two main configurations: direct-loop systems (direct systems) and closed-loop systems (indirect systems) [6].
Direct-loop marine heat pump systems are characterized by the direct circulation of seawater through the heat pump, resulting in recognized efficiency gains and energy savings. However, their efficiency is very low in cold regions, where operation is interrupted due to pipe corrosion and seawater freezing.
Closed-loop marine heat pump systems overcome these problems through the use of a submerged heat exchanger that separates the heat pump from the seawater. This configuration includes three distinct fluid circuits operating simultaneously: a circuit for cooling within the heat pump, a circuit for the intermediate fluid that exchanges heat with seawater via the submerged heat exchanger, and a circuit for the transport water that carries the thermal energy to the building.
Table 1 presents the main differences between open-loop and closed-loop marine heat pump systems.

Table 1. Comparison of open-loop and closed-loop seawater-source heat pump system configurations.

Feature	Open-loop System	Closed-loop System
Seawater–unit contact	Direct	Indirect
General efficiency	Higher; favored by ASHRAE standards and widely adopted by engineering companies in Europe and the United States	Lower energy consumption required, as the system does not need to overcome seawater transport resistance

Performance in cold regions	Very low; system operation may be halted due to pipe corrosion and seawater freezing	Maintained; avoids freezing and corrosion phenomena through indirect contact with seawater
Energy consumption for fluid transport	Higher; must overcome seawater transport resistance	Lower; no seawater transport resistance required
Intermediate fluid	Seawater directly	Water–ethylene glycol mixture (e.g., 25 wt.%, freezing point −13 °C)
Corrosion risk	High	Low (indirect contact with seawater)
Freezing risk	High (seawater freezing point ≈ −1.7 °C at 3‰ salinity)	Low (glycol mixture prevents freezing)
Fluid loops	Single loop (seawater circulates directly through the heat pump unit)	Three distinct loops: refrigerant loop, intermediate fluid loop, and transport water loop

As shown in Table 1, the closed-loop configuration offers greater operational reliability in cold climates, at the cost of a slightly more complex fluid circuit.

4 Heat Exchangers

To improve the performance of marine heat pump (MHP) systems, it is necessary to optimize the geometric configurations and working fluids of their heat exchangers. The following text summarizes recent advances in diverse heat exchanger configurations applied to the marine environment.
Table 2 presents a comparison based on the main materials, performance indicators, and limitations for the five heat exchanger configurations examined.

4.1 Double-pipe helical heat exchanger

The experimental investigation of alumina/water nanofluids in a double-pipe helically coiled heat exchanger demonstrated that nanoparticle concentration has no significant effect on the critical Reynolds number. A novel correlation was formulated for laminar heat transfer in a hysteresis pipe that anticipates the experimental value.

The outcomes display how the thermal transfer improvement of nanofluids is more than 0.37%, determined by a steady flow velocity. This modest gain is attributed to the mitigation of secondary flow intensity induced by centrifugal forces inherent to the helical geometry resulting from the higher viscosity and density of the nanofluid, effects that may offset the benefit of increased thermal conductivity [7].

4.2 Nanofluid heat exchanger

The experimental study mentioned the change of the heat pump system by preparing six various mass fractions of graphene nanofluids (0~1 wt.%) that increased heat transfer in heat exchangers below invariable temperature conditions of seawater. The results revealed that low concentrations (0.01~0.1 wt.%) provided the best performance, as the heat transfer enhancement effect outweighed the viscosity-induced resistance.

However, at higher concentrations (0.5~1 wt.%), the sharp increase in viscosity exceeded the thermal conductivity gain, causing a significant decrease in both convective heat transfer coefficient and exergy transfer effectiveness [8].

4.3 Staggered tube-bundle heat exchanger

In a seawater heat pump system, a staggered tube-bundle heat exchanger with unequally-pitch arrangement (USTP) was implemented using an aluminum alloy with a thermal conductivity of 107 W/m·K, this material reduces the thermal resistance of the tube walls to less than 5% of the total thermal resistance, making it a non-dominant factor in the heat transfer process.

The results of the experimental study showed that the overall heat transfer coefficient ranges from approximately 35% to 38%, while the thermal efficiency is 30% to 33%, these values for the USTP are higher than those of the double-pass heat exchanger configuration with equal pitch, as this type of USTP configuration also exhibits a 15% reduction in pressure drop, which highlights the USTP's superior performance in terms of overall thermal, hydraulic, and thermo-hydraulic performance [9].

4.4 Capillary box heat exchanger

A novel marine heat pump technology is devised using capillary box heat exchangers (CBHEs) buried in the seabed as the front-end heat exchanger. Field experiments confirmed that even under extreme cold/hot climate conditions, the 24-hour COP and EER of the heat pump unit reached respectively 2.96 and 5.39, which is superior to an equivalent air-source heat pump. A three-dimensional unsteady-state seepage and heat transfer model was established to examine the thermal performance of CBHEs using ANSYS FLUENT software.

The results showed that the thermal conductivity of the backfilled sand is the most influential factor, with a mean sensitivity 1.7 times higher than that of seawater seepage velocity [10]. Furthermore, increasing the seawater seepage velocity in the seabed by 7 times only results in a heat extraction rate increase of 1.56 times, while the numerical simulation showed that raising the flow velocity in capillary tubes by 4 times yields a 29.2% gain in heat extraction rate and a 31.4% rise in heat rejection rate. The recommended flow velocity is between 0.08 and 0.1 m/s [10].

4.5 Plate heat exchanger

An empirical study was conducted in Qingdao, China, to examine the technical and economic performance of a seawater heat pump system incorporating an intermediate heat exchanger that acts as a barrier between the seawater and the heat pump unit. This device also helped to protect the system against corrosion and reduce the need for anti-corrosion protection. The study showed that this type of indirect heat exchange system reduces the initial cost of the heat pump by approximately 18.81% and ensures a life-cycle cost (LCC) that is 4.16% lower than that of a direct heat exchange system, with a payback period of 9.1 years.

However, this addition is not always beneficial, as this heat exchanger reduces energy efficiency by 9.63% and increases annual operating costs by 6.98%. The two configurations are similar in terms of economic indicators such as net present value, LCC, annual cost and payback period. This intermediate heat exchanger configuration offers superior technical reliability, a longer service life and a more viable solution for marine environments [11].

Table 2. Comparative Overview of Heat Exchanger Technologies for Marine Heat Pump Systems.

Heat Exchanger Type	**Material / Working Fluid**	**Key Performance Results**	**Main Limitation**
Double-pipe helical	Alumina/water nanofluid (0.78–7.04 wt%); copper inner tube; d_i = 13.28 mm	Heat transfer enhancement: 0.37%–3.43% vs. water (constant velocity basis); laminar correlation coefficient of determination R^2 = 0.995	Nanofluid viscosity reduces secondary flow intensity, partially neutralizing thermal conductivity benefit; modest net enhancement
Nanofluid-based (coaxial tube)	Graphene nanofluid (GnP, 0–1 wt%); nickel-copper tube; heat exchange area = 1.9 m²	Best exergy transfer effectiveness at 0.01–0.1 wt%; at 1.0 wt%, viscosity reaches 3× base fluid, causing sharp drop in convective heat transfer coefficient	Optimal concentration range is narrow; performance degrades significantly above 0.1 wt%
Staggered tube-bundle (USTP)	Aluminium alloy; λ = 107 W/(m·K); tube outer diameter = 16 mm; unequally-pitch arrangement	Overall heat transfer coefficient and thermal efficiency 35–38% and 30–33% higher than equally-pitch arrangement; pressure drop reduced by ~15%	Inhomogeneous pitch geometry increases fabrication complexity; validated in oscillating flow only
Capillary box (CBHE)	Polypropylene random (PPR) capillary tubes (outer diameter = 4.3 mm); 30% glycol solution; coarse sand backfill	24-h COP = 2.96; EER = 5.39; 13% higher COP and 41.1% higher EER than equivalent air source heat pump (ASHP)	Performance highly dependent on backfill sand thermal conductivity (sensitivity 1.7× > seepage velocity)
Plate heat exchanger (IHE)	Plate-type intermediate heat exchanger; 15% ethylene glycol; Rated effectiveness = 0.65	SCOP_heating = 3.72; SCOP_cooling = 3.22; life cycle cost reduced by 4.16% and initial heat pump unit cost reduced by ~18.81% vs. direct exchange	Energy efficiency penalty of 9.63%; annual operating cost increases by 6.98%

The comparative analysis in Table 2 highlights that while nanofluid-based and staggered tube-bundle configurations offer notable heat transfer enhancements, each technology presents specific trade-offs between thermal performance, fabrication complexity, and operating cost.

5 Performance

The performance of marine heat pump (MHP) systems is evaluated based on three key criteria: energy performance, environmental performance, and economic performance.

5.1 Energy performance

Seawater heat pumps constitute a district heating system that offers greater energy efficiency than a conventional heating system powered by a coal-fired boiler, provided that its average seasonal coefficient of performance exceeds a critical minimum threshold. This threshold can be determined by comparing the total energy consumption of the two systems during the heating season, taking into account the efficiency of converting coal into electricity, the average efficiency of the boilers, and the electrical consumption of the pumps relative to the total heat supplied. A study conducted in Dalian, China, showed that the critical coefficient of performance (COP) is 2.58, compared to an actual average seasonal COP of 3.36, indicating a potential energy saving of 23.21%, and a result of 20.56% obtained using the conventional static method [12].

5.2 Environmental performance

Environmental performance is assessed using two key indicators: CO_2 emissions intensity and $PM_{2.5}$ emissions intensity, both expressed per kilowatt-hour of heat supplied. In Shanghai, in southern China, heat pumps reduce CO_2 emissions by up to 72% and $PM_{2.5}$ emissions by 79% compared to the district heating system using electric coal-fired boilers. Northern China, represented by the city of Qingdao, has been characterized by the dominance of coal-fired electricity generation, accounting for over 97% of the total; air-source heat pumps (ASHPs) have reduced CO_2 emissions by 24% and $PM_{2.5}$ emissions by 24%, whereas ground-source heat pumps led to a significant reduction in CO_2 emissions of 43% and $PM_{2.5}$ emissions of 41% compared to district heating using coal-fired boilers.

The sensitivity analysis showed that air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs) which achieved a minimum seasonal coefficient of performance (SCOP) of 2.46 to achieve neutrality in terms of CO_2 and $PM_{2.5}$ emissions, $_5$ compared to coal-fired boilers, and this demonstrates that increasing the share of renewable electricity helps to reduce the emission potential of heat pump systems [13].

5.3 Economic performance

Economic performance is measured using the discounted payback period (DPP), which represents the time required for the seawater heat pump (SWHP) system to recoup the additional initial investment compared to an air-source heat pump (ASHP) system. In a study of 29 coastal cities, the DPP is less than 20 years, which is also the system's lifespan, with a minimum of 5.66 years for Hangzhou and a maximum of 10.43 years for Weifang.

The payback periods for southern coastal cities have an average payback period of approximately 6.85 years for Jiangsu Province and southern cities, but this payback period is longer, at 8.96 years, for Shandong Province and northern cities. The difference in payback periods between southern and northern cities is explained by the higher sea water temperatures in the southern regions, which help to improve system efficiency, reduce annual operating costs and accelerate the return on investment [14].

Table 3 consolidates the key performance indicators discussed across the three dimensions of evaluation.

Table 3. Key performance indicators of seawater-source heat pump systems.

Dimension	Performance Indicator	Value
Energy	Seasonal COP (COPh,ma) – Dalian, heating season average	3.36
	Critical minimum COP (COPh,mc) vs. coal boiler heating system	2.58
	Energy saving potential vs. boiler house (quasi-dynamic method)	23.21 %
Environmental	CO_2 emission reduction vs. electric heater (Shanghai)	72 %
	$PM_{2.5}$ emission reduction vs. electric	79 %

	heater (Shanghai)	
	Minimum SCOP required for CO_2 neutrality vs. coal boiler	2.46
Economic	Discounted Payback Period (DPP) – 29 coastal cities	5.66 – 10.43 yrs
	Average DPP – Northern coastal cities (Shandong and above)	8.96 yrs
	Average DPP – Southern coastal cities (Jiangsu and below)	6.85 yrs

Table 3 shows that seawater heat pump systems offer significant benefits in terms of energy savings, reduced CO2 emissions, and cost savings.

6 Challenges

The performance of marine heat pump (MHP) systems is limited by physical and chemical factors that cause damage to system components due to the harsh marine environment.

6.1 Seawater temperature

The thermal properties of seawater, such as its temperature, play a significant role in ensuring the efficiency of marine heat pump systems, particularly in the process of extracting heat from the marine environment. The study carried out on the Liaodong Peninsula in China involved field measurements for two water intake configurations: a direct intake system operating at an average seawater temperature of 5.83°C and an average unit coefficient of performance (COP) of 2.99; in contrast, the beach well infiltration system, with an average inlet temperature exceeding 12.85°C and an average unit COP of 4.66.

This is explained by the fact that the beach well draws from deeper underground seawater layers, characterised by higher temperatures than those of the surface direct intake system. This makes the beach well infiltration system more reliable in terms of operational stability, system reliability and energy efficiency, making it well suited to cold climates [15].

6.2 Seawater fouling

Seawater fouling is a phenomenon that prevents the effective passing of thermal energy and economic losses. Micro/nanoscale surface variation has emerged to diminish the negative effects of fouling by exploiting titanium, silicon, polymers, and amorphous carbon. These micro/nanoscale surface profiles serve to decide surface-foulant interfaces. These surface topographies play a decisive role in governing surface-foulant interactions, and surface energy has been identified as a critical parameter: low surface energy surfaces are generally favorable for early foulant removal under fluid shear forces [16].

6.3 Corrosion

Seawater desalination facilities are characterized by a highly corrosive environment, making the choice of materials a critical issue, especially in regions with hot climates where seawater temperatures are higher, thereby increasing the risk of material degradation. For this reason, this issue must be taken into account during the design phase. For seawater reverse osmosis (SWRO) systems, stainless steels are the standard choice based on their pitting resistance index (PREN).

However, insufficiently alloyed grades such as UNS S31603 (316L) and UNS S31703 (317L) can lead to serious failures caused by pitting corrosion and crevice corrosion. Even highly alloyed stainless steels are not suitable for the challenges of the hostile marine environment. The risk of corrosion and its severity depend on several interrelated factors, such as: the chemical composition of the alloy, the manufacturing process, operating conditions, and the geometries of confined areas that are in frequent contact with seawater [17].

6.4 Thermal pollution

The discharge of hot water causes thermal pollution, leading to a localized increase in surface water temperature; the intensity of this thermal impact depends heavily on the season and the plant's capacity. Seasonal variation is marked by a peak in summer due to rising temperatures and a trough in winter due to the presence of ice. Thermal pollution disrupts the ecological balance of coastal ecosystems including phytoplankton, zooplankton, macrobenthos, and aquatic fauna which amplifies the effects of global warming, particularly at the local level [18].

Table 4 provides a structured overview of the four main challenges: seawater temperature, biofouling, corrosion, and thermal pollution, detailing their mechanisms, operating conditions, and impacts on heat exchanger performance.

Table 4. Main challenges affecting heat exchanger performance in marine heat pump systems.

Challenge	**Mechanism**	**Aggravating Conditions**	**Impact on Heat Exchanger Performanc**

			e
Seawater temperature	Seasonal/diurnal thermal variability; depth-dependent	High seepage velocity; shallow intake depth; cold climate regions	COP fluctuation; risk of freezing and operational shutdown
Seawater fouling	Marine organism deposition on heat exchanger surfaces	High surface energy; elevated temperature; low flow velocity	Increased thermal resistance; reduced heat transfer coefficient
Corrosion	Chloride-induced pitting and crevice corrosion	T >20°C; seawater stagnation; tight crevice geometry; insufficient PREN	Material degradation; failure of pumps, valves, and piping
Thermal pollution	Warm water discharge into coastal waters	High installed capacity (> 2000 MW); summer season; shallow water depth	Ecosystem disruption; amplified local warming effects

Table 4 showed that these challenges are closely interrelated: corrosion, biofouling, and thermal pollution are all caused by rising seawater temperatures, which creates feedback loops that must be addressed holistically.

7 Discussion

Heat exchangers are used in several technologies, such as marine heat pumps, which enable heating and cooling using the thermal energy of seawater, making them a renewable alternative to these technologies. However, the harsh conditions of the marine environment cause problems that reduce the energy performance of the system. Among these challenges are: the unstable temperature of seawater depending on the season, location and day (morning, night); corrosion of materials caused by the salinity of seawater, which leads to the gradual degradation of components; and biological fouling caused by the sedimentation of marine plants.

These challenges require rapid and effective solutions to maintain the energy and environmental efficiency of these technologies in terms of their carbon footprint, ensuring they operate without generating greenhouse gas emissions while taking into account their impact on the marine environment. Among these solutions are the development of new materials that can withstand marine conditions characterized by higher temperatures and salinity, the design of new heat exchanger geometries that optimize the exchange surface and energy transfer, the improvement of new fluids such as the use of nanofluids, which are obtained by suspending nanoparticles or nanotubes in conventional fluids, increasing thermal transfer because of the thermal conductivity of the nanoparticles compared to their base fluids.

Finally, these marine heat pump heat exchanger technologies require research and development of solutions that take into account marine environment conditions, investment, operating and maintenance costs, the marine environment, and also heat exchanger materials and designs, while striving to move from research to practical application.

8 Conclusion

This study demonstrated that marine heat pump heat exchangers are an alternative technology that utilizes renewable energy considered on seawater but encounters several problems that cause a decrease in their energy performance. These challenges include corrosion caused by salinity, biological fouling caused by the sedimentation of marine components, and variations in seawater temperature, which make the system unstable and disrupt the marine environment.

We need to implement some solutions, for example, new materials, innovative configurations of heat exchangers, and new fluids, while improving effective maintenance methods and taking into account the necessary costs and the impact of the solutions on the marine environment.

It is recommended to seek to develop intelligent solutions to achieve adequate maintenance with prediction of fault locations in these technologies, and also to study the impact of products that prevent corrosion and biofouling, without forgetting to study their effects on the marine environment, such as biotic and abiotic systems. It is also necessary to find suitable environments for installing these technologies, studying variations in seawater temperature for injection and infiltration systems.

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