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ORIGINAL

A Unified Review of Thermal System Optimization and Automation Technologies Shaping Modern Marine and Oil-Gas Engineering

Una revisión unificada de las tecnologías de automatización y optimización de sistemas térmicos que configuran la ingeniería marina y de petróleo y gas moderna

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ABSTRACT

Thermal management and automation have become closely linked factors that drive innovation across marine propulsion systems and oil-gas engineering. This review indicates that the contemporary changes in heat-exchanger design, energy-efficient cooling strategies, and data-driven control architectures are redefining the performance levels that were expected in both sectors. For the marine sectors, the recent research shows that the focus is shifting towards the use of compact, high-flux thermal exchangers and hybrid cooling loops which have the capability to adjust to fluctuating onboard loads as well as meet stringent environmental regulations. Similarly, oil and gas works are going on to install more automated sensing, predictive diagnostics, and intelligent process control for stabilising thermal behaviour under harsh operating conditions. As a result of examining these innovations from a single perspective, the review points out the merging engineering principles - in particular, system-level optimisation, real-time monitoring and digitally supported decision-making - that are most likely to be the characteristics of the next-generation energy and fluid-handling infrastructures. The integration, therefore, volunteers that knowledge transfer from one sector to another may be the main factor that will lead the way to the engineering systems that are more resilient, efficient, and environmentally responsive at a faster rate. The latest marine heat exchangers primarily focus on a compact and efficient design that can be durable for a long time even in a harsh environment. This review paper explores the recent changes in design methods, performance enhancement techniques, material selection, and computer modeling strategies. It also highlights the problems of fouling, scaling, corrosion, and maintenance difficulties, which are major barriers to performance at a high level. In addition, this research identifies potential research themes such as the implementation of eco-friendly design principles, digital monitoring and predictive maintenance technologies, and additive manufacturing for the creation of custom and efficient heat exchanger parts. These innovations, in combination, provide the platform for the subsequent set of marine cooling solutions.

Keywords: Thermal System Optimisation; Marine Cooling Technologies; Oil–Gas Engineering; Real-Time Monitoring; Digital Engineering; Sustainable Industrial Operations.

RESUMEN

La gestión térmica y la automatización se han convertido en factores estrechamente vinculados que impulsan la innovación en los sistemas de propulsión marina y la ingeniería de petróleo y gas. Esta revisión indica que los cambios actuales en el diseño de intercambiadores de calor, las estrategias de refrigeración energéticamente eficientes y las arquitecturas de control basadas en datos están redefiniendo los niveles de rendimiento esperados en ambos sectores. En el sector marino, investigaciones recientes muestran que el enfoque se está desplazando hacia el uso de intercambiadores térmicos compactos de alto flujo y circuitos de refrigeración híbridos, capaces de adaptarse a las fluctuaciones de las cargas a bordo y de cumplir con las estrictas normativas ambientales. De igual manera, las plantas de petróleo y gas están implementando sistemas de detección más automatizados, diagnósticos predictivos y control inteligente de procesos para estabilizar el comportamiento térmico en condiciones operativas adversas. Al examinar estas innovaciones desde una perspectiva única, la revisión señala los principios de ingeniería integrados —en particular, la optimización a nivel de sistema, la monitorización en tiempo real y la toma de decisiones con soporte digital— que probablemente caracterizarán las infraestructuras de energía y manejo de fluidos de próxima generación. Por lo tanto, la integración, que permite que la transferencia de conocimiento de un sector a otro, sea el factor principal que impulse sistemas de ingeniería más resilientes, eficientes y respetuosos con el medio ambiente a un ritmo más acelerado. Los intercambiadores de calor marinos más recientes se centran principalmente en un diseño compacto y eficiente que ofrece una larga vida útil incluso en entornos hostiles. Este artículo de revisión explora los cambios recientes en métodos de diseño, técnicas de mejora del rendimiento, selección de materiales y estrategias de modelado informático. También destaca los problemas de incrustaciones, incrustaciones, corrosión y dificultades de mantenimiento, que constituyen importantes barreras para un rendimiento óptimo. Además, esta investigación identifica posibles temas de investigación como la implementación de principios de diseño ecológicos, tecnologías de monitorización digital y mantenimiento predictivo, y la fabricación aditiva para la creación de piezas de intercambiadores de calor personalizadas y eficientes. Estas innovaciones, en conjunto, sientan las bases para el futuro desarrollo de soluciones de refrigeración marina.

Palabras clave: Optimización de Sistemas Térmicos; Tecnologías de Enfriamiento Marino; Ingeniería de Petróleo y Gas; Monitoreo en Tiempo Real; Ingeniería Digital; Operaciones Industriales Sustentables.

INTRODUCTION

Marine cooling systems represent the thermal core of both seaborne and offshore engineering operations, thus they always keep the propulsion engines, the auxiliary machinery, and the onboard power-generation units in a stable working condition. Their main role is to control the temperatures in the engines and in the equipment that are used for different loads and under changing weather conditions all the while while making sure that the temperatures do not go beyond the allowed limits. These devices prevent the vessels from overheating, so they are still able to do the same under the prolonged exposure that is typical of ocean-going vessels, mechanical wear is kept at a minimum, combustion efficiency is improved, and the service time is extended. At the center of this setup is the heat exchanger that regulates the heat transfer from the sea, lubricating oils, and the specially engineered coolant mixtures. But the severe marine environment that includes the corrosive saltwater exposure, biological fouling, and unstable thermal loads is always a challenge for the design and operation of

the systems. As a result, the drop in efficiency has a chain effect on the engine power, fuel consumption, emission characteristics, and the maintenance planning in the long run.[1,2,3,4] The recent materials engineering and thermal efficiency improvements have substantially changed the marine heat exchanger design concept. The use of high-durability materials like titanium and Cu–Ni composites as well as quite new corrosion-resistant polymers have indicated not only the improvement of thermal conductivity but also the extension of the service life. Some issues of CFD and CAE methods have been solved at the same time they have been developed which means now they allow very precise studies of complex flow fields, finding the thermal hot spots, and the optimisation of the geometry taking place long before the manufacturing process. Additionally, additive manufacturing is speeding up the transition by making it possible to produce small exchangers with the complex internal channels that are impossible to be done traditionally. Notwithstanding these improvements, some problems still linger: foulings, scalings, and corroding, which are the main reasons for the decrease of the efficiency in heat-transfer and that are leading to the increasing maintenance costs. The implementation of economical marine operations has driven the requirements to be met for cooling systems to be even more environmentally friendly with the introduction of predictive monitoring systems and real-time data analytics for their support.[5,6,7,8] Similarly in the oil and gas industry, limited resources have led to an equally fast development of innovations in thermal management and emission control technologies. The industry is confronted with increasing regulatory pressures to lower emissions from the use of fossil energy and to optimize consumption patterns in accordance with carbon-neutral economic targets. Thermal systems are instrumental in stabilizing compressor trains, refining units, pumping networks, and vapor-handling operations in upstream, midstream and downstream facilities. Most importantly, it is the thermal characteristics of volatile organic compounds (VOCs) that need to be tightly controlled to avoid evaporative losses and reduce the release of harmful gases to the atmosphere. Research on gasoline terminals and tanker operations indicates that temperature has a major effect on VOC emission rates, thus local thermal and automated control strategies need to be implemented in tandem. Several sources elaborate on the use of modern vapor recovery devices including membrane-based capture systems and gas-dynamic cooling units, which are utilized to recover hydrocarbons in an efficient manner while at the same time allowing for the least amount of thermal energy losses to take place.[9,10,11,12,13] Automation and digitization have continually changed thermal optimisation through oil and gas operations. Advanced sensing platforms, real-time emission monitoring, and intelligent decision-support systems allow operators to predict thermal anomalies before they turn safety or efficiency failures.[14,15] The use of CFD to redesign shell-and-tube and plate heat exchangers has led to the substantial increase of thermal efficiency in the application of high-pressure syngas cooling, refinery heat recovery, and pipeline processing.[16,17] All of these alterations are leading towards one very clear trend: the integration of thermal-system optimisation, emissions control, and automation is becoming a fundamental engineering concept in both marine and oil–gas environments. By using predictive analytics, material innovation, and computational optimisation, the thermal infrastructures of the future will not only be more maritime but also hydrocarbon operations. They will be able to exhibit higher resilience, lower energy consumption, and less environmental impact. The thermal optimisation of oil–gas facilities is becoming increasingly tightly linked with emissions control, in particular, the management of volatile organic compounds (VOCs) that are generated during the storage, loading, and transport of hydrocarbons. The release of VOCs is very much dependent on temperature, and if there is inadequate thermal control, evaporation losses will accelerate thus increasing fire risks and amplifying environmental impacts as well. Recent surveys of gas stations and terminals reveal that monitoring demands have been gradually getting more stringent, while emission reductions have mainly been the consequence of improved thermal regulation and automation-assisted

detection systems.[18] The study on marine VOC recovery has come to the same conclusions about the challenges of shipboard environments, where tank temperatures change and the sea is inconstant, thus making vapor-handling processes difficult.[19] Technological methods like hollow-fibre membrane absorbers and advanced cooling-assisted vapor recovery units (VRUs) are effective in stabilising hydrocarbon temperatures while capturing evaporated fractions.[20,21] These devices, when coupled with predictive optimisation tools and digital sensors, can significantly diminish losses and be in line with the global low-carbon and sustainability directives.[22] A significant movement in both marine and oil–gas engineering is the merging of digital thermal-management technologies, in which the core system components are real-time data acquisition, machine-learning-enabled diagnostics, and automated control loops. On the offshore and subsea installations, the scope of automation has been broadened from simple process control to include thermal anomaly detection, equipment-level prognostics, and automated load balancing under challenging operational conditions.[23] Likewise, corresponding systems that employ onboard digital platforms to monitor heat-exchanger degradation, detect the fouling initiation, and suggest the adaptive operating strategies are now being implemented in marine cooling systems.[24] The integration of CFD-assisted design tools, smart monitoring, and closed-loop control results in an integrated thermal-performance ecosystem that can not only predict but also adapt. As oil–gas industries transition to energy-efficient, low-emission infrastructures, these common digital methods along with advanced materials and Additive Manufacturing are going to be the major drivers of cross-sector innovation. Eventually, this convergence implies that marine and hydrocarbon industries are moving to a single engineering paradigm that is thermal efficiency, operational reliability, and environmental compliance are co-engineered from the very beginning.

METHOD

Types of Marine Heat Exchangers

Marine heat exchangers are designed to locally cool the main engines, the auxiliary machinery and the onboard power system, and become generally several types depending on their material of construction and flow arrangement. Shell-and-tube exchangers are the most common, employing bundles of tubes housed in a cylindrical shell to absorb heat from seawater to the cooling liquids, thereby giving off long life and easy servicing. Plate heat exchangers intensify the heat exchange area by using a number of corrugated metal plates stacked together and thus achieving the most efficient heat transfer in the smallest spaces, which are the most suitable for vessels with strict weight and size limitations. Spiral and helical exchangers use a coiled portion to keep the flow turbulent and hence less fouling, thus they are the ones that can be used in the polluted water environments. Finned and compact exchangers further increase heat transfer efficiency by increasing the surface area and are most likely to be found in marine systems with great performances or limited space. More advanced configurations, such as microchannel and hybrid exchangers, provide better heat transfer and less coolant requirements, thus they are capable of meeting the modern energy efficiency, low emissions and marine environmental standards requirements.[6,7]

Table 1. Types of Marine Heat Exchangers vs Applications

Type of Marine Heat Exchanger	Description	Typical Applications on Ships
Shell and Tube Heat Exchanger	Consists of a series of tubes inside a shell; fluids flow through the tubes and shell side for heat exchange.	Main engine jacket cooling system Lube oil cooler Freshwater cooler

late Type Heat Exchanger (PHE)	Made of thin corrugated metal plates; compact, high heat transfer efficiency.	Central cooling system Auxiliary engine cooling Freshwater–seawater heat exchange
Air Cooled Heat Exchanger (Radiator Type)	Uses air as cooling medium instead of seawater; fans used for heat dissipation.	Generator engine cooling HVAC condensers on smaller vessels
Spiral Heat Exchanger	Spiral-shaped channels provide high heat transfer efficiency and easy cleaning.	Sludge oil heating Fuel oil heating
Double Pipe (Tube-in-Tube) Heat Exchanger	One fluid flow inside the inner tube, another between the inner and outer tubes.	Small auxiliary systems Lube oil cooling for small engines
Plate Fin Heat Exchanger	Uses fins between plates to increase surface area; compact and lightweight.	Refrigeration and air conditioning systems Gas–liquid heat recovery
Condenser (Marine Steam System)	Converts exhaust steam from turbines into water by seawater cooling.	Steam propulsion plants Auxiliary steam systems

Cooling Systems

Shell-and-tube heat exchangers

The factors that mainly contributed to the retention of shell-and-tube heat exchangers as the leaders in the market include their strength, versatility, and energy-efficient working mode. These characteristics are typical for processes where heat exchange is performed between two fluids accompanied by no direct mixing. The latter feature is especially important for cases, where the contamination of the liquid can not only significantly influence the chemical reactions, but also the quality of the final product and even its safety.[1] Their most common utilizations have been: the condensing and cooling of power plants, the cooling of marine engines, climate control through HVAC systems, and temperature regulation in the chemical and petrochemical industries, which is very helpful in many chemical reactions for stability and energy saving purposes. The reason of the shell-and-tube heat exchangers long-lasting and diverse applications rely on their ability to withstand a very broad range of operating conditions - from high-pressure and extreme temperatures (very high or very low) to large liquid flow rates - and still maintain a consistent thermal performance Shell-and-tube heat exchanger fundamentally consists of the cylindrical-shaped outer shell which encloses a bundle of tubes. [2] Normally, one liquid is allowed to flow through the tubes, while the other liquid is passed over the outside of the tubes but still within the shell. The tubes are the intermediaries in heat exchange between the two liquids and at the same time, they separate them, so no mixing of the fluids takes place. This is convenient for those operations in which the mixture may lead to contamination, corrosion, or the formation of some unwanted chemical reactions. The liquid in the tubes may be allowed to flow through the heat exchanger only once or may be made to have multiple passes.[3] The point that it can be built to have either single or multiple pass flow arrangements allows the engineer to come up with not only the best solution for heat transfer rate, pressure drop, and efficiency of a certain system but also the process requirements and space available. An essential element in the design of shell-and-tube heat exchangers is the decision to fit baffles. Baffles are the pieces that are fixed in the shell and their function is to change the direction of fluid, which is flowing through the shell, by pushing the fluid across the tubes instead of letting it go straight from the inlet to the outlet. Baffles, that cause crossflow and turbulence, are the main contributors to the heat transfer efficiency.

Besides that, they stop the happening of both hot spots and stagnation regions in the shell. There exist various baffle designs such as segmental, helical, and disk-and-doughnut and the choice of each depends on factors like the flow pattern, heat exchange goals, and allowable pressure drop. For instance, the segmental baffles, which are mostly used because of their simple structure and good turbulence production, provide efficient mixing. However, helical baffles have more powerful effects on the elimination of dead zones and less wear due to vibration.[4]

Due to their modular design, they can be taken apart, cleaned, and repaired much more easily than other heat exchangers.[6] In most cases, the removal of tube bundles is possible, after which they are cleaned by mechanical or chemical methods and reinstalled with a minimum of downtime which makes the shell-and-tube designs a cost-effective solution in the long run. In addition, modern maintenance programs that include the online monitoring of temperature differentials and pressure drops provide operators with the opportunity to recognize the first stages of fouling and take the action to solve the problem before that. As a result, shell-and-tube heat exchangers have ranked their position as one of the major components of the industrial thermal engineering systems alongside their robustness, versatility, and very good performance. Their strong build enables them to be combined with extreme temperature and pressure changes while their adaptability with tube arrangement, baffle arrangement, flow patterns, and material selection can be modified for practically any process.

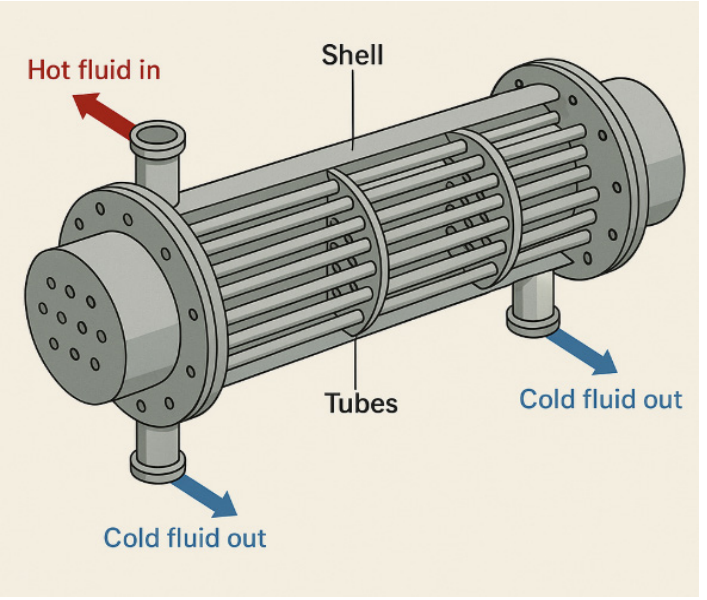


Figure 1. Shell-and-tube heat exchangers

In case these devices are regularly taken care of and materials are wisely chosen, they will deliver long-term reliability and trouble-free operation, which is energy efficiency, process safety, and decrease of operational costs.[7] In the case of fluid mixing, heat transfer is possible through these devices and their modularity makes inspection and cleaning simple, thus being a reason why, out of numerous different classes of exchangers, the shell-and-tube kind as shown in figure 1 is amongst the most used and reliable ones in modern industrial and marine applications.

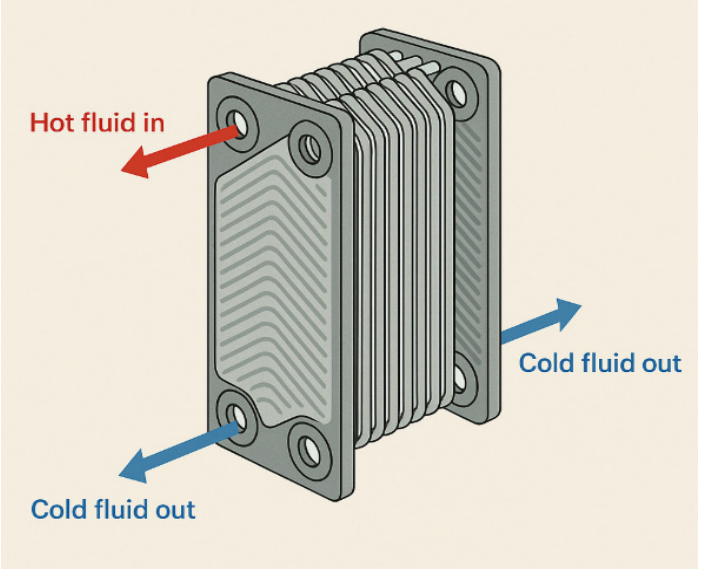


Figure 2. Plate heat exchangers

Spiral and compact designs

Spiral heat exchangers as shown in figure 3 are a type of heat exchangers that are very efficient.

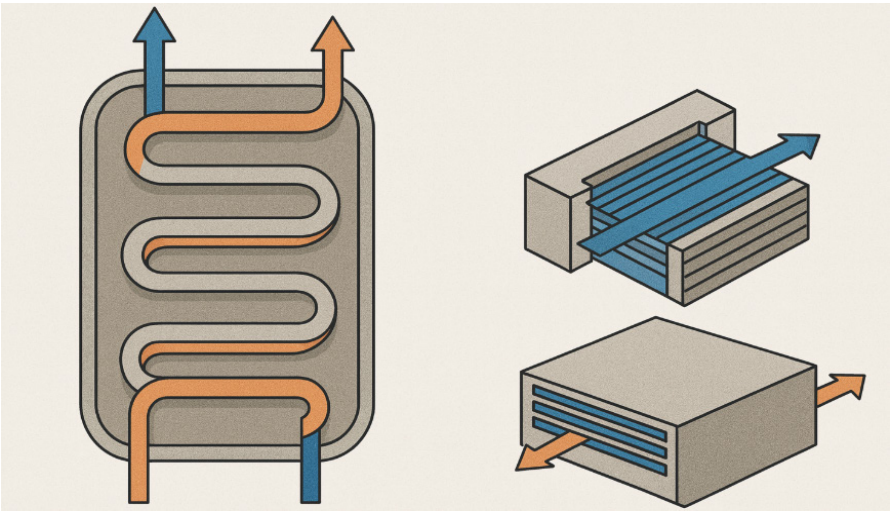


Figure 3. Spiral and compact designs

They are notable for their compactness, low fouling, and excellent thermal performance practically in any industry, over a wide range of temperatures and other operating conditions. The basic idea of the chamber structure is the turning of two flat metal sheets one above the other around a central core in such a way that two concentric spiral channels for the flow - one for the hot fluid and the other for the cold - will be formed. It is an extremely efficient way of heat transfer as each fluid will go through one continuous spiral path without any interruption from the inlet to the outlet. The spiral geometry provides several natural/practical advantages

over more traditional types like shell-and-tube or plate heat exchangers.[11] The most important advantage of the spiral heat exchanger at present is the large surface area-to-volume ratio produced by the spiral windings. Because the flow paths are long and tightly coiled, a significant part of the heat transfer surface area is exposed to the fluids in a small footprint. In fact, this device attains maximum heat transfer between fluid and surface, thereby increasing overall thermal efficiency and at the same time, the unit size is decreased and therefore less material is needed.

Hybrid and microchannel exchangers

Hybrid heat exchangers are a technological breakthrough that essentially represent the next level of thermal-exchange evolution. They can effectively combine the advantages of disparate heat exchanger designs into a single, integrated unit.

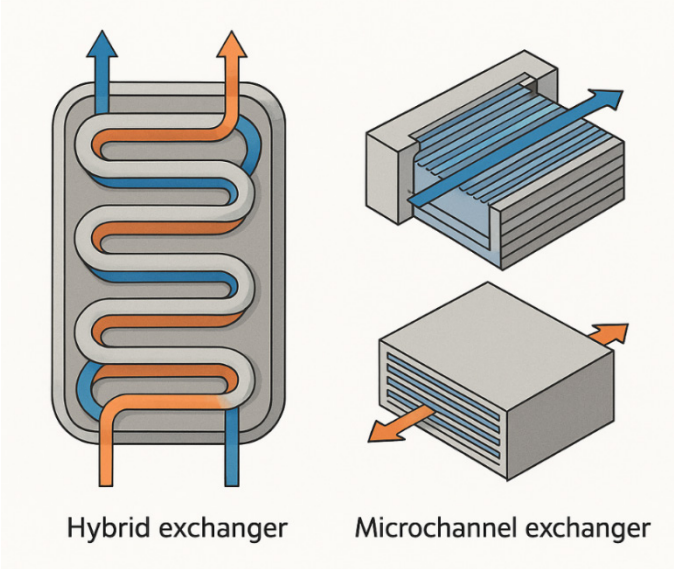


Figure 4. Hybrid and microchannel exchanger

By combining the features of different layouts in a very precise manner, hybrid exchangers can show the characteristics of a performance which a standard unit of a single type can hardly achieve.[15] Most illustrative in this regard is the example of a plate and shell hybrid which integrates thin, corrugated heat-transfer plates with a cylindrical pressure shell. The corrugated plates create very small flow channels which keep the flow turbulent and the surface-area-to-volume ratio high, therefore they achieve very high heat-transfer coefficients typical of plate-type exchangers as demonstrated in figure 4. Meanwhile, the outer cylindrical shell provides the mechanical strength necessary to withstand high pressures and temperature conditions, as those are normally encountered in industrial processes.

Enhancement methods vs. Reported Efficiency Gains

Enhancement strategies for marine and industrial heat exchangers are aimed at lifting the heat-transfer rates, lowering the pressure drops, and lessening the fouling, with reported efficiency improvements that go to different extents depending on the method and the conditions of operation. Usually, surface modification techniques like corrugated plates, finned tubes, or dimpled surfaces provide 10–30 % of the improvement by increasing the turbulence and the effective area. The thermal performance of the device could be increased by 20–50 %

with flow-induced enhancement methods which include helical baffles, spiral channels, and swirl generators, however, it could be a higher pumping power that is the cost sometimes. In some cases, such as compact or high-temperature systems, material-based enhancements including high-conductivity alloys or nanofluid coolants, have demonstrated 15–40 % efficiency gains. By reasons like optimized flow distribution and very high surface-area density, advanced methods like microchannel structures or additive-manufactured geometries normally result in 30–70 % improvements. In the end, hybrid combined enhancement methods—merging geometry, material, and flow strategies—can exceed efficiency gains of 70 % thus revealing the strong synergy between classical thermal engineering principles and novel high-performance technologies.

Table 2. Enhancement methods vs. Reported Efficiency Gains

Enhancement Method	Description	Reported Efficiency Gain / Performance Improvement
Finned Tubes	Addition of fins on tube surfaces to increase heat transfer area.	20–50 % increase in overall heat transfer coefficient.
Corrugated /Chevron Plates	Wavy plate design in plate heat exchangers creates turbulence and improves mixing.	30–70 % improvement in heat transfer rate compared to flat plates.
Twisted Tape Inserts	Helical tape inserted into tubes to induce swirl flow and turbulence.	25–60 % rise in convective heat transfer; pressure drop increases.
Nano fluids	Use of nanoparticles (Al_2O_3, CuO, TiO_2, etc.) in the working fluid to enhance thermal conductivity.	10–40 % higher heat transfer coefficient (depends on nanoparticle type/ concentration).
Surface Roughening / Dimpled Surfaces	Creating dimples or rough surfaces on heat transfer walls to promote turbulence.	15–35 % increase in Nusselt number; minor pressure losses.
Helical / Spiral Flow Passages	Curved flow paths increase secondary flow and mixing.	20–45 % better heat transfer effectiveness.
Use of Phase Change Materials (PCM)	Incorporating PCM for latent heat storage to smooth out temperature variations.	10–25 % improvement in thermal energy utilization efficiency.
Enhanced Flow Distribution (Baffles, Vortex Generators)	Improves mixing and prevents dead zones in shell or plate channels.	15–40 % rise in heat transfer coefficient.

Enhancement Methods vs. Reported Efficiency Gains in Oil & Gas Thermal Systems

The heat exchangers that are impacted by these severe situations in the oil and gas industry require the application of enhancement methods which do not only uphold their reliability but also increase their thermal efficiency in the whole refineries, offshore platforms, LNG units, and petrochemical plants. In these processes, surface-modification techniques like finned tubes, dimpled plates, and corrugated geometries are widely employed in crude preheaters, gas coolers, and stabilization units, that often achieve 10-30 % gains as a result of turbulence promotion and heat-transfer surface area extension as shown in figure 5 and table 3.

Enhancement Method	Reported Efficiency Gains
Surface Modification	10–30%
Flow-Induced	20–50%
Material-Based	15–40%
Advanced Design	30–70%

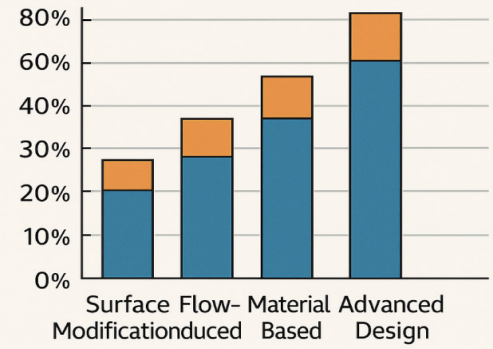


Figure 5. Enhancement Methods vs. Efficiency Gains

Flow-induced enhancements such as helical baffles, twisted-tube bundles, and swirl generators are particularly potent in viscoelastic fluids like crude oil or glycol mixtures where they yield 20-50 % improvements while also removing the stagnant zones that lead to fouling. Besides that, material-based methods like copper-nickel alloys, titanium composites, and nanofluid-enhanced coolants open up the room for additional efficiency increases of 15-40 % in high-pressure sour-gas streams, LNG vaporisers, and offshore produced-water coolers.[20,21,22]

Table 3. Enhancement Methods Used in Oil & Gas Thermal Systems

Enhancement Method	Oil & Gas Application	Typical Efficiency Gain
Surface Modification	Crude preheaters, gas coolers	10–30 %
Flow-Induced	Offshore glycol coolers, crude exchangers	20–50 %
Material-Based	Sour-gas coolers, LNG vaporizers	15–40 %
Advanced Design	Subsea compression, refinery compact exchangers	30–70 %

Oil Industry Performance & Optimization Insight

Advanced enhancement techniques, such as microchannel architectures and additive-manufactured exchanger blocks, are gaining traction subsea compression systems, high-density refinery exchangers, and compact gas-treatment skids. These innovations achieve 30–70 % greater efficiency, lower coolant needs, and improve thermal uniformity—very important for the prevention of coke formation in heavy-oil processing or thermal shock in LNG operations as shown in figure 6 y table 4. Hybrid solutions combining surface geometry, advanced materials, and optimized flow paths usually deliver the highest performance, with the potential of over 70 % improvements, most notably in catalytic reformers, amine regeneration units, and regenerative crude preheaters. Together, these upgrades enable oil and gas facilities to cut fuel consumption, stabilise process temperatures, and comply with increasingly tight emissions and energy-efficiency regulations.[24]

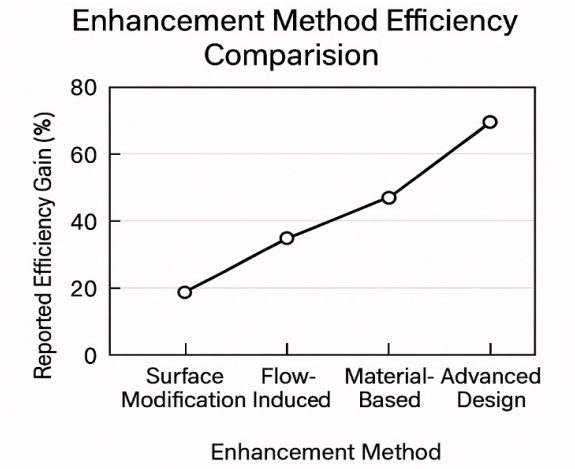


Figure 6. Enhancement Method Efficiency Comparison

Table 4. Performance Gains Observed in Oil-Related Case Studies

System Type	Enhancement Technique	Reported Improvement
Crude Distillation Unit	Helical baffles	+42 % heat-transfer rate
LNG Process Cooler	Microchannel block	+65 % thermal efficiency
Offshore Heat Recovery	Finned tubes	+28 % energy recovery
Petrochemical Reactor Cooling	Nanofluid coolant	+37 % heat-transfer coefficient

RESULT AND DISCUSSION

Performance Challenges in Marine Environment for Fixed Tube Sheet (Streight) Heat Exchanger

The standard society marine industry shell-and-tube heat exchangers with fixed tube-sheet, straight-tube is the most common design as shown in figure 7. The main reasons for their selection are their simple construction, small volume, and strength. When all these factors are combined, they become the most suitable systems for vessels, floating production/storage/offloading units, and other sea-going installations where high reliability, long service life, and easy-to-integrate limited space are the most logical criteria.[13] However, if the performance and lifetime of heat exchangers are indifferent, the marine environment will still be able to harm them.

Unlike most industrial systems onshore, marine heat exchangers need to withstand the dynamic motions, fluctuating operating conditions, and harsh environmental factors simultaneously - this combination of factors makes the equipment significantly more stressed. Under such circumstances, it is quite necessary to put the facility in its best condition both in terms of design and operation if the criteria of safety, efficiency, and long-term reliability are to be fulfilled. Problems caused by marine vibration and dynamic loading are rarely at the top of the list that most of the problems resulting in the chain of events below are. The situation is such that vessels as well as floating production/storage/offloading units undergo several types of movements (e.g. heaving, pitching, and rolling) to which changes in flow rates and transient operational conditions are added. The forces generated by these movements reach the heat exchanger through the structural supports and piping, thus they cause flow-induced vibration, resonance, and fatigue of the tubes.[15] In fixed-tube-sheet arrangements where the tubes on both ends are tightly attached to both tube sheets, the tube bundles actually become more rigid

as the bundle cannot move separately to absorb the displacement caused by the movement. Incorrect baffle spacing, absence of anti-vibration supports, or too long span of the tubes between the baffles may cause wear which may, in turn, lead to the wear-related occurrence of fretting, fatigue, or loosening of the tube-to-tube-sheet joint areas as a result of the wear that has been caused by the factors mentioned above.

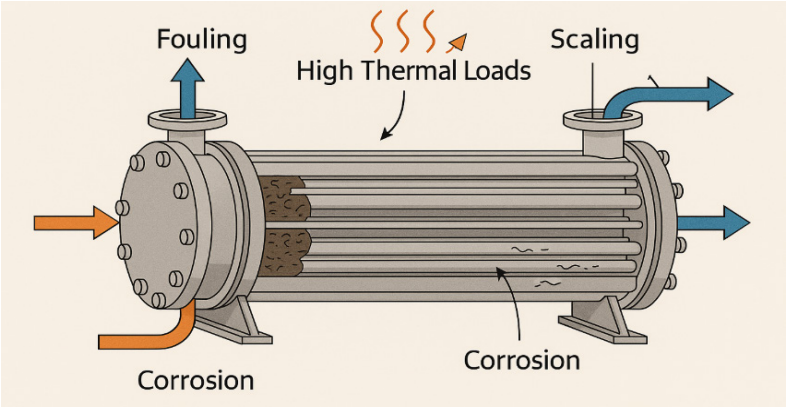


Figure 7. Fixed Tube Sheet Heat Exchanger

Comparative Studies and Benchmarking for Fixed Tube Sheet Heat Exchanger

In essence, fixed tube-sheet (straight-tube) heat exchangers in oil and gas operations remain the focal point of comparative studies that emphasize their reliability, minimal space requirement, and ability to handle a broad spectrum of crude, condensate, and process-cooling tasks as shown in figure 8. Performance-mapping studies reveal that the straight-tube layout ensures stable heat exchange even under moderate fouling and thermal load conditions. Such devices, therefore, find their uses as refinery pre-heaters, desalters, gas-oil coolers, and produced-water exchangers. Yet, in a head-to-head comparison with floating-head, U-tube, or spiral-wound designs, straight-tube heat exchangers are more likely to exhibit a lesser degree of tolerance to differential thermal expansion and a higher propensity for the tube-side to be coated with the deposition of, e.g., heavy crude fractions or high-salinity brines. Benchmarking schemes take various measures to quantify efficiency such as the overall heat-transfer coefficient (U), pressure drop, fouling factor progression, and open-to-closed-cycle maintenance. In crude stabilization and offshore process trains, straight-tube heat exchangers are usually able to perform 10–20 % less of their thermal efficiency as compared to advanced spiral or helical ones but are still the first choice of solution in situations where mechanical simplicity, high-pressure containment, and cost-effective deployment are needed.[21] Fixed tube sheet exchangers also reveal in detail operational limitations directly from their harsh chemistries of hydrocarbons, dissolved gases, and corrosive seawater that is usually used in cooling circuits in oil-sector benchmarking studies. Heavy oils, waxy crudes, and asphaltene-rich streams are leading the tube-side fouling process, while high-chloride water is intensifying the corrosion risks at the tube sheet interface, thus most of the times the service life of the exchangers is the one that is going to be compared to the alloy-based or plate-type configurations. Modern comparative analyses focus heavily on choosing materials—like duplex stainless steel, Cu–Ni alloys, or titanium—as the major factor that can result in almost double the lifetime of offshore and downstream units. Besides, the benchmarking done at refineries and petrochemical complexes indicates that the performance difference of advanced exchanger types can be reduced by the use of flow-distribution baffles, tube inserts, and cleaning schedules optimization. In those operations which are highly dependent on thermal processes like catalytic reforming and LNG

precooling, straight-tube exchangers are still able to hold a competitive position when they are upgraded through CFD-based redesign and predictive fouling monitoring. Thus, they become a cost-efficient, strong benchmark choice for oil and gas facilities that have to strike a balance between the performance demands and maintenance and economic constraints.[22]

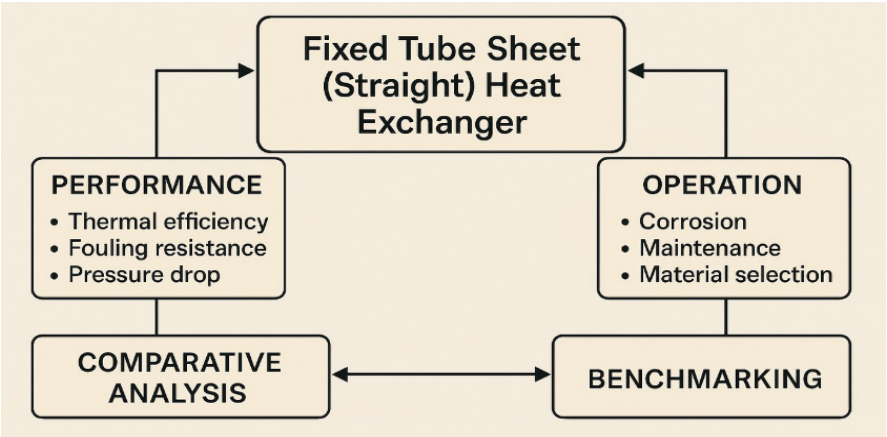


Figure 8. Comparative Studies and Benchmarking for Fixed Tube Sheet

Future Research Directions for Fixed Tube Sheet (Straight) Heat Exchanger

It is possible to anticipate that most of the changes or improvements in fixed tube sheet (straight) heat exchangers will result from innovations in material technology, the addition of digital monitoring systems, and the use of eco-friendly design strategies. In order to satisfy the requirement of a service life in the marine and offshore environments under aggressive chloride exposure, it is expected that more corrosion-resistant and thermally conductive alloys such as duplex stainless steels, titanium grades, and advanced Cu–Ni blends will be typical. By way of example, the additive manufacturing and precision-engineered geometries may open up the more effective flow distribution and lessened fouling by which the maintenance challenge caused by heavy oils, seawater cooling, and high-particulate streams has been solved for a long time.

At the same time, the deployment of smart sensors, real-time fouling prediction models, and machine-learning-based performance dashboards will drastically change the methods used for monitoring and maintaining these exchangers. The implementation of digital twins, condition-based cleaning, and remote operation frameworks will not only reduce the times of shutdown but also increase the thermal stability of refinery, LNG, and offshore platforms. In addition, global sustainability requirements will be a factor that pushes the industry to implement low-energy cooling methods, to embrace hybrid exchanger configurations, and to take up modular designs that reduce emissions and increase the overall plant efficiency. Taken together, these imminent changes illustrate a shift towards heat exchanger systems for the marine and oil-gas industries that are highly resilient, digitally optimized, and environmentally compliant.

CONCLUSIONS

The fixed tube sheet heat exchanger with straight tubes continues to be the most popular choice in the industrial and marine sectors, especially in oil and gas processing, because of its simple construction, long service life, and relatively cheap fabrication. The tubes are fixed in the tube sheets that are welded to the shell, thus the joints are strong and leak-tight which also makes tube-side cleaning easy—a feature that is very helpful when dealing with stabilized

crude, produced water, or clean condensate streams. The design with its small size and easy fabrication is also well suited for the execution of steady-state duties involving relatively clean fluids and moderate thermal gradients, like those met in utility cooling, lube-oil systems, and refinery heat-recovery loops. On the other hand, this design that features a fully restrained tube arrangement also has some significant risks. In oil-sector operations where temperature swings are considerable—such as during crude preheating, amine regeneration, or gas-oil cooling—the lack of tube expansion capability can lead to high thermal stresses at the tube-to-tube-sheet interface, which is a main cause of failure in many offshore and refinery case studies. Furthermore, limited access to the shell side makes mechanical cleaning difficult; therefore, this design is not suitable for services where the shell side is likely to foul with heavy crude, waxy fractions, brine contaminants, or solids-bearing produced fluids. Hence, fixed tube sheet exchangers should only be used when the shell-side media are clean and the operating conditions are within moderate limits. The engineers are increasingly using the optimized baffle configurations, better surface treatments, and advanced tube geometries in order to overcome the drawbacks of the oil applications and thus achieving higher performance. These measures help to alleviate thermal stress and fouling problems while at the same time maintaining the inherent advantages of the heat exchanger.

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CONFLICT OF INTEREST

None.

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