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Printed-Circuit Heat Exchangers for Nuclear Marine Propulsion: A Compact Steam Generation Solution

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1. Introduction

As the global community accelerates decarbonization efforts, the maritime industry faces increasing pressure to transition away from fossil fuels. Given that shipping accounts for approximately 3% of global greenhouse gas emissions [1], regulatory bodies such as the International Maritime Organization (IMO) have adopted a revised GHG strategy targeting net-zero emissions by or around 2050, with interim checkpoints for 2030 and 2040. Among the proposed alternatives, nuclear propulsion has emerged as a viable solution due to its high energy density, long operational endurance, and zero direct CO_2 emissions [2].

The adoption of marine nuclear reactors presents a compelling opportunity to achieve sustainable, high-power propulsion while reducing dependence on fossil fuels. However, one of the foremost challenges in realizing nuclear-powered vessels is the reduction of reactor size to enable practical shipboard integration [3]. To make nuclear propulsion feasible for widespread use, the development of ultra-compact, high-performance reactors is imperative. Advances in small modular reactors (SMRs) and advanced reactors offer promising solutions, but further innovation in reactor miniaturization, shielding optimization, and thermal efficiency is essential. Addressing these challenges will be critical to ensuring the practical adoption of nuclear propulsion in the commercial maritime sector, enabling a new era of low-emission, high-endurance global shipping.

2. Compact Designs for Nuclear-Powered Ships

2.1 Space Limitations in Ships

Maritime vessels must adhere to strict dimensional constraints to ensure safe passage through major canals and ports worldwide. For instance, the Panama Canal, one of the most important global shipping routes, enforces the following size restrictions [4]:

- Maximum Length Overall (LOA): 289.6 meters (~950 feet) for most ships, with certain ships permitted up to 294.43 meters (~966 feet).
- Maximum Beam (Width): 32.31 meters (~106 feet), with an absolute limit of 32.61 meters (~107 feet).
- Maximum Draft (Submerged Depth): 12.04 meters (~39.5 feet) for Panamax ships and up to 15.2 meters (~50 feet) for New Panamax ships.

Beyond canal transit, the International Maritime Organization (IMO) sets safety and structural guidelines for ship design. Nuclear-powered vessels must integrate propulsion systems without exceeding critical width or height constraints, ensuring stability, fuel storage, and emergency response capabilities are not compromised.

2.2 Deployment of reactors (RITM-200)

To integrate nuclear propulsion into ships, reactors must be compact, lightweight, and space-efficient, ensuring they fit within the constraints of modern vessel design. The RITM-200, developed by OKBM Afrikantov, is one of the most advanced marine nuclear reactors, specifically designed for icebreakers and potential commercial ships. It features a 6m × 6m footprint with a height of 15.5m, allowing it to be installed in ships without exceeding width constraints or significantly altering hull structures [5]. Compared to conventional marine reactors like the KLT-40S, the RITM-200 is 45% smaller and 35% lighter, making it an ideal solution for vessels with limited space for reactor compartments and shielding systems. Given that ships like Panamax-class vessels have a maximum beam of 32.31m and height limits around 57.91m, the RITM-200 remains well within feasible integration limits, particularly in engine rooms or below the superstructure.

A key innovation in the RITM-200's compact design is the integration of steam generators within the reactor vessel, eliminating the need for large external piping and secondary loops, which are common in conventional pressurized water reactors (PWRs). This not only reduces the reactor's footprint but also enhances thermal efficiency and safety by minimizing potential leak points. Additionally, the reactor operates with a high-power density of 175 MWt, providing sufficient propulsion power for large icebreakers and potentially future nuclear-powered cargo ships. Another critical feature is its extended fuel cycle of 7–10 years, which reduces refueling frequency, ensuring long-term operation with minimal downtime, a crucial factor for high-endurance maritime applications.

The successful deployment of the RITM-200 in Russia's Project 22220 nuclear icebreakers, including Arktika (2020), Sibir (2022), and Ural (2022), has demonstrated the feasibility of compact marine nuclear reactors in large-scale commercial vessels. The reactor's design aligns with modern shipbuilding constraints, making it a strong candidate for future nuclear-powered merchant ships, particularly in Arctic and long-range maritime transport. As global shipping moves toward low-emission solutions, innovative compact reactors like the RITM-200 provide a viable pathway to sustainable and high-efficiency nuclear propulsion in commercial fleets.

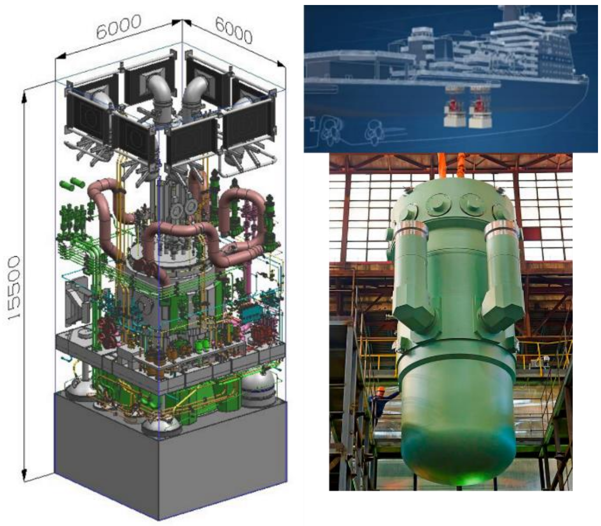

Fig. 1. Arrangement and picture of RITM-200.

3. Compact Steam Generator

In marine nuclear propulsion systems, compact steam generators are crucial due to the limited space available on vessels. It transfers heat from the reactor's primary coolant to the secondary system, producing steam that drives turbines for propulsion and electricity generation. A compact design not only optimizes space but also enhances efficiency and safety by reducing the length of piping and potential points of failure. This spatial efficiency is essential for accommodating other critical systems and maintaining the vessel's stability and performance.

3.1 Once-Through Helical Coiled Steam Generator (OTHSG)

The Once-Through Helically Coiled Steam Generator (OTHSG) is one of the most widely used steam generator designs in marine reactors and SMRs. Its helical coil configuration enables a compact, high-performance heat exchanger, ideal for the limited space available on ships and submarines. Unlike traditional recirculating steam generators, which require large separators to maintain phase stability, the OTHSG operates with a once-through flow system, meaning the secondary coolant passes through only once, undergoing a direct phase transition to steam. This improves thermal efficiency, enhances reactor responsiveness, and eliminates the need for bulky steam separators, making it highly suitable for dynamic marine environments.

Several reactor designs currently employ the OTHSG due to its space-efficient and high-performance characteristics [6]:

- IRIS (International Reactor Innovative and Secure) – An integral pressurized water reactor (iPWR) designed by Westinghouse, using OTHSG for its compact and simplified design.
- SMART (System-integrated Modular Advanced Reactor) – A small modular reactor (SMR) developed by KAERI (Korea Atomic Energy Research Institute), using OTHSG for compact integration within its integral reactor vessel.
- NuScale SMR – A leading U.S. SMR design, where OTHSG is integrated inside the reactor pressure vessel, minimizing external piping and enhancing safety.
- KLT-40S (Russia's floating nuclear reactor) – Used in nuclear icebreakers and floating power plants, equipped with OTHSG to maximize space efficiency.

Although the OTHSG is more compact than traditional steam generators, its current design remains insufficient for widespread use in nuclear-powered ships beyond submarines and icebreakers. While the helical coil structure enhances heat transfer efficiency and allows for integration into SMRs and iPWRs, it still occupies significant space and has notable pressure drop issues, which limit its application in high-power marine reactors. For next-generation nuclear-powered vessels, including cargo ships and advanced naval ships, an even higher power density and more compact steam generator design are essential. To address this, research is focusing on alternative technologies such as Printed Circuit Heat Exchangers (PCHEs), which offer a significantly smaller footprint, improved heat transfer efficiency, and better structural integrity, making them a promising candidate for future marine nuclear propulsion systems.

3.2 Printed Circuit Heat Exchanger (PCHE)

The Printed Circuit Heat Exchanger (PCHE) is a next-generation heat exchanger technology originally developed for aerospace and chemical industries but now being explored for nuclear applications, including marine reactors. Unlike conventional shell-and-tube steam generators or even OTHSGs, PCHEs use chemically etched microchannels in stacked metal plates, which are then diffusion-bonded to form a compact, high-strength heat exchanger. This design enables extremely high surface-area-to-volume ratios, leading to superior heat transfer efficiency in a smaller footprint.

Incorporating PCHEs into nuclear marine propulsion offers several advantages:

- Ultra-Compact Size – PCHEs can be 10 times smaller than traditional heat exchangers, fitting within the strict spatial constraints of ships.
- High Thermal Efficiency – The microchannel structure significantly enhances heat transfer, allowing for better performance at lower coolant flow rates.
- Extreme Pressure Resistance – PCHEs can withstand pressures exceeding 20 MPa, making them suitable for advanced high-temperature reactors and supercritical CO_2 cycles.
- Structural Integrity – The diffusion-bonded plates eliminate mechanical joints, reducing the risk of thermal fatigue and leaks, a critical advantage for marine reactors operating in extreme environments.

However, challenges remain before PCHEs can be fully adopted in nuclear marine propulsion. Fouling and clogging of microchannels pose maintenance difficulties, requiring advanced cleaning methods like chemical flushing and ultrasonic cleaning. Additionally, PCHEs lack long-term operational experience in nuclear applications, necessitating further testing and regulatory validation. Despite these challenges, PCHEs represent a promising future alternative to traditional OTHSG-based steam generators, offering a potential breakthrough in compact and high-performance nuclear propulsion systems for commercial and military ships.

4. Feasibility studies of PCHE as Steam Generator

4.1 MIT - IRIS

A study conducted at MIT explores the advantages of adopting PCHEs over OTHSGs for iPWRs. The research highlights that OTHSGs, despite their compact nature compared to traditional steam generators, still occupy a significant footprint due to their helical tube arrangement. PCHEs, with microchannel-based designs and diffusion-bonded plates, offer a substantially higher surface-area-to-volume ratio, allowing for greater heat transfer in a significantly smaller space. The study focuses on optimizing the thermal performance of PCHEs, demonstrating their potential to enhance the efficiency of steam generation systems in advanced reactor designs.

Simulation results show that PCHEs outperform OTHSGs in both heat transfer efficiency and system compactness. The results indicate that PCHEs achieve up to 30% higher heat transfer efficiency while occupying 60% less volume compared to OTHSGs. Additionally, the pressure drop in PCHEs is reduced by approximately 40%, leading to lower pumping power requirements and overall system energy savings. The study also examines temperature distribution and flow uniformity, demonstrating that PCHEs maintain more stable heat exchange performance across varying operating conditions, making them a more robust solution for integral reactor designs requiring compact and efficient steam generators.

Applying PCHE technology to the IRIS design could yield significant improvements in reactor compactness and performance. The IRIS reactor currently employs OTHSGs for steam generation within its integral vessel, but replacing them with PCHEs could reduce the steam generator’s volume by nearly 50%, allowing for a more compact reactor pressure vessel while maintaining or even enhancing thermal efficiency. This transition would not only improve the feasibility of IRIS for smaller, space-constrained applications but also enhance its operational efficiency, fuel economy, and thermal safety margins, making it a stronger candidate for next-generation SMR applications.

4.2 Georgia Tech – I^2S-LWR

A study on Integral Inherently Safe Light Water Reactor (I2S-LWR) highlights the benefits of using microchannel heat exchangers (MCHX) instead of conventional tubular steam generators. The MCHX-based steam generator, developed using diffusion-bonded microchannel technology, provides a more compact and structurally efficient solution compared to traditional once-through helically coiled steam generators (OTHSGs). The reactor's downcomer region, where the primary-to-secondary heat exchangers are placed, has spatial constraints requiring highly compact designs. The study demonstrates that MCHXs offer a higher surface-area-to-volume ratio, reducing the overall footprint while enhancing heat transfer performance.

Simulation results indicate that MCHX achieves a thermal efficiency of 39.0%, surpassing the 34.58% efficiency of OTHSG-based Rankine cycles. The study also shows that MCHXs reduce pressure drop significantly, with a secondary-side pressure drop of only 9.5 kPa, compared to the higher values seen in tubular steam generators. Additionally, MCHX improves temperature uniformity and minimizes exergy losses, leading to better overall system efficiency. The enhanced performance is attributed to microchannel flow characteristics, which improve heat transfer coefficients while reducing fluid pumping requirements.

Applying MCHX technology to the IRIS reactor could provide substantial improvements in size reduction and power generation efficiency. Replacing the conventional OTHSG design with MCHX could reduce the steam generator volume by nearly 50%, making the reactor pressure vessel (RPV) more compact and enhancing thermal safety margins. This transition would significantly improve the feasibility of IRIS as a marine propulsion reactor, aligning with industry demands for higher power density and compact nuclear systems.

5. Conclusions

The need for compact, high-efficiency steam generators is a crucial challenge in marine nuclear propulsion, where spatial constraints, thermal efficiency, and operational safety must be carefully balanced. While

OTHSGs have been the standard choice, their limitations in power density, pressure drop, and overall size create barriers to their adoption in a broader range of nuclear-powered vessels. This study identifies the PCHE as a game-changing alternative, offering unmatched heat transfer performance, smaller volume, and improved structural integrity. By integrating PCHEs into marine nuclear reactors, designers can significantly reduce system size and weight while maintaining high efficiency, paving the way for next-generation compact nuclear propulsion systems.

The MIT study on the IRIS reactor provided concrete evidence of PCHE's superior performance over OTHSGs. Simulations revealed that PCHEs achieved 30% higher heat transfer efficiency, reduced reactor volume by 60%, and decreased pressure drop by 40%. These improvements indicate that if PCHEs were integrated into IRIS, the reactor vessel could be significantly downsized, making the system more adaptable for naval and commercial nuclear-powered ships. The ability to reduce reactor footprint while improving efficiency positions PCHEs as a breakthrough technology for future marine propulsion reactors.

Further validation comes from the Georgia Tech study on I2S-LWR, which demonstrated that PCHE-based steam generation increased thermal efficiency from 34.58% (OTHSG) to 39.0%, while also reducing secondary-side pressure drop to 9.5 kPa. This substantial performance enhancement proves that PCHEs are not just an incremental improvement but a transformative solution for marine nuclear systems requiring higher power density and compact reactor designs. As nuclear propulsion becomes more critical in the push for carbon-free maritime transport, PCHEs provide a highly efficient, space-saving, and structurally robust option for the next generation of nuclear-powered vessels.

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