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Review of Comparison of Heat Transfer and Pressure Drop between OTHSG and PCHE

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1. Introduction

The growing demand for carbon-neutral energy has accelerated the development of Small Modular Reactors (SMRs), which emphasize safety, economic efficiency, and modular scalability. A key component of SMRs is the steam generator, which impacts thermodynamic efficiency, system compactness, and reactor performance.

Two leading SMR steam generator candidates are the Once-Through Helically Coiled Steam Generator (OTHSG) and the Printed Circuit Heat Exchanger (PCHE). OTHSG, widely used in designs like IRIS and SMART, offers compactness and high heat transfer efficiency, while PCHE, originally from aerospace and chemical industries, is gaining attention due to its ultra-compact design, high-pressure tolerance, and superior heat transfer capabilities [1,2].

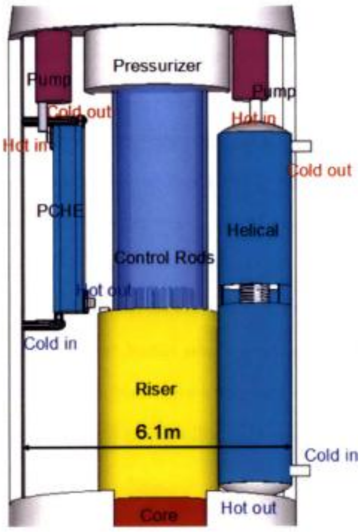

Fig. 1. Example of a Comparative Analysis Between PCHE and OTHSG in an SMR Configuration [2]

Although both technologies have promising characteristics, they also have limitations. OTHSG is a proven technology but requires more volume and may struggle in extreme high-pressure environments. PCHE reduces reactor vessel size and enhances thermal efficiency, but its nuclear application remains in early stages, with concerns over manufacturing, pressure drop, and long-term reliability.

As SMRs move toward commercialization, conducting a comparative analysis of OTHSG and PCHE becomes essential. By reviewing existing studies, this research examines their thermohydraulic performance, design feasibility, and suitability for next-generation SMRs, providing insights for selecting the most efficient and reliable steam generator

2. Once-Through Helically Coiled Steam Generator (OTHSG)

OTHSG is a widely employed heat exchanger in nuclear power plants, particularly in integral pressurized water reactors (iPWRs) and SMRs. This type of steam generator is designed to efficiently transfer heat from the primary coolant, typically high-temperature and high-pressure water, to the secondary coolant, which is converted into steam. OTHSG consists of helically coiled tubes, through which the primary coolant flows, while the secondary coolant moves in a counterflow direction, allowing for effective heat exchange. The helical configuration enhances thermal performance while enabling compact integration within the reactor vessel, a crucial advantage for SMRs where space optimization is critical.

2.1 Design and Operational Principles

OTHSG employs a once-through flow system, meaning that the secondary coolant passes through the system only once, absorbing heat and converting into steam without requiring recirculation. Unlike typical steam generators, which depend on steam separators to maintain phase stability, OTHSG enables a continuous phase transition along the helical tube length, thereby enhancing thermal performance [3].

2.2 Advantages and Disadvantages

OTHSG is widely utilized in reactor designs due to its high heat transfer performance, compact structure. However, it also presents several challenges, including difficulties in tube maintenance and constraints on reactor vessel design. Additionally, despite its compactness compared to conventional steam generators, OTHSG still requires a relatively large volume, making its integration into maritime applications challenging.

3. Printed Circuit Heat Exchanger (PCHE)

PCHE is an advanced heat exchanger technology that has gained significant attention in next-generation nuclear reactor designs, particularly in SMRs. Originally developed for aerospace and chemical industries, PCHEs offer superior heat transfer performance, compact design, and high-pressure resistance, making them a promising alternative to conventional steam generators such as OTHSGs. Unlike conventional shell-and-tube heat exchangers, PCHEs are characterized by their microchannel structure, which maximizes heat transfer efficiency by increasing the surface-area-to-volume ratio [4].

3.1 Design and Operational Principles

PCHE consists of multiple layers of metal plates, where each plate has precisely chemically etched mini/microchannels that guide the flow of primary and secondary coolants. These plates are stacked together and diffusion-bonded, creating a highly compact and mechanically strong heat exchanger that can withstand extreme pressure and temperature conditions. The microchannel configuration allows for enhanced turbulence, significantly improving heat exchange efficiency [5].

One of the defining characteristics of PCHE is its counterflow arrangement, where hot and cold fluids flow in opposite directions. This design ensures that the temperature difference between the two fluids remains large along the entire flow path, thereby maximizing heat transfer effectiveness. Additionally, the high thermal conductivity of the metal plates further enhances heat dissipation, allowing PCHEs to handle high-temperature gradients efficiently.

PCHEs are designed to operate under ultra-high pressures, typically exceeding 20 MPa, which makes them particularly suitable for supercritical CO_2 and helium-cooled reactor applications [6]. Their ability to withstand such conditions is due to the diffusion bonding process, which eliminates mechanical joints and welds, thereby improving structural integrity and reducing failure risks associated with thermal cycling.

3.2 Advantages and Disadvantages

The microchannel-based design of PCHE significantly enhances heat transfer performance by inducing turbulence and improving thermal mixing, even at low Reynolds numbers. This allows PCHE to achieve superior efficiency compared to shell-and-tube heat exchangers, even with lower coolant flow rates. Additionally, PCHE's strong structural integrity and resistance to extreme pressures and temperatures make it well-suited for supercritical reactors, helium-cooled reactors, and high-temperature gas-cooled reactors (HTGRs).

Furthermore, PCHE minimizes pressure drop through optimized flow paths, improving overall system efficiency compared to conventional heat exchangers, which often suffer from significant pressure losses.

However, PCHE faces technical challenges, including fouling and maintenance difficulties due to its small mini/microchannels (<5 mm), which are prone to clogging by corrosion products and impurities. Advanced cleaning techniques such as chemical flushing and ultrasonic cleaning are required to maintain long-term performance. Additionally, PCHE as steam generator lacks long-term operational experience in nuclear reactors, necessitating further research to validate its reliability.

4. Comparative Analysis of OTHSG and PCHE

OTHSGs and PCHEs are among the most promising candidates for use in nuclear reactor systems, particularly in SMR designs. Each technology offers distinct advantages and presents unique challenges. This section provides a detailed comparison of OTHSG and PCHE, examining their structural differences, heat transfer performance, pressure drop characteristics, operational feasibility, and maintenance considerations. The following analysis summarizes research conducted at MIT, particularly focusing on 1D analysis, incorporating key findings to provide a comprehensive evaluation of these heat exchanger technologies.

Table I: Comparative Analysis of Primary and Secondary Side Parameters for OTHSG and PCHE [3]

Parameters	**Helical**	**PCHE**	
power	125	125	MW
Primary side:			
Mass Flow rate	589	589	Kg/s
Mass Flux	897	1276	Kg/m2s
Inlet Temperature	328.4	328.4	C
Outlet Temperature	292	291.9	C
Inlet Pressure	15.5	15.5	MPa
Pressure drop	72	64	kPa
H Transfer Coefficient	6,843	56,057	W/m2K
Secondary side			
Mass Flow rate	62.5	62.5	Kg/s
Mass Flux	693	135	Kg/m2s
Inlet Temperature	223.9	223.88	C
Outlet Temperature	317	319.95	C
Outlet Pressure	5.8	5.8	MPa
Pressure drop	296	77	MPa
H Transfer Coefficient	130,160	466,755	W/m2K
Geometry			
Diameter	variable	0.002	m
Width	-	0.6	m
Height	7.9	4.2	m
Length(core)	-	0.277	m
Volume (no headers)	65	0.7	m3
Volume w/headers	70	1.45	m3
Volume Ratio	48.28	0.02	-
Surface Area Density	44.5	1420	m2/m3
Power Density	1.92	178.57	MW/m3

4.1 Heat Transfer Performance

Heat transfer performance is a critical factor in selecting an appropriate heat exchanger for nuclear reactors. PCHE demonstrates superior heat transfer efficiency due to its microchannel structure, which enhances turbulence and convective heat transfer even at lower Reynolds numbers. This results in higher local heat flux, particularly in the nucleate boiling regime. However, the presence of a sharp heat flux peak indicates a pronounced dry-out phenomenon, where the liquid film evaporates completely, leading to a rapid decline in heat transfer performance beyond a certain point. Managing this dry-out behavior is crucial for ensuring the long-term reliability of PCHE-based steam generators.

In contrast, OTHSG relies on a helical flow path to induce secondary flows that enhance heat transfer. While its turbulence levels are lower than those of PCHE, the heat flux distribution remains more uniform, and dry-out effects are less severe. This results in a more stable thermal performance, reducing the risk of sudden heat transfer degradation. Additionally, the larger channel size in OTHSG leads to a lower surface-area-to-volume ratio, limiting its overall heat transfer efficiency.

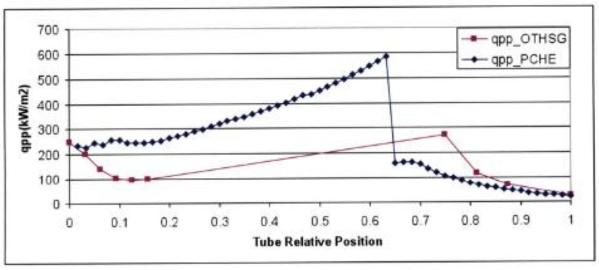

Fig. 2. Example of Heat Flux Distribution Comparison Between PCHE and OTHSG [3].

4.2 Pressure Drop Comparison

Pressure drop is a significant factor influencing pumping power requirements and overall system efficiency. OTHSG generally experiences pressure drops due to the helical flow path, which increases flow resistance and introduces additional frictional losses. The curvature of the tubes enhances secondary flow effects but also contributes to higher pressure losses, necessitating careful hydraulic optimization.

PCHE, in contrast, has significantly smaller microchannels, which inherently result in higher local pressure drops per unit length. However, due to its superior heat transfer efficiency, a PCHE-based system can achieve the same thermal output with a more compact design. This reduction in overall system size offsets the localized pressure drop increase, ultimately leading to a lower total pressure drop compared to an equivalently rated OTHSG. As a result, PCHE facilitates energy-efficient operation by reducing overall pumping power requirements, making it advantageous for systems where minimizing auxiliary power consumption is a priority.

3. Conclusions

The comparative analysis of OTHSGs and PCHEs demonstrates that PCHE offers superior compactness, heat transfer efficiency, and pressure drop minimization, making it well-suited for SMRs despite its manufacturing complexity and maintenance challenges. While OTHSG benefits from passive safety mechanisms through natural circulation, its larger footprint and lower heat transfer efficiency make it less favorable for advanced nuclear reactor designs prioritizing miniaturization and high performance.

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