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Printed Circuit Heat Exchanger Structure and Characteristics Research Review

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Abstract

Printed Circuit Heat Exchangers (PCHE) are a type of compact heat exchanger known for their strong heat transfer capabilities and high temperature and pressure resistance. In recent years, they have shown potential applications in next-generation nuclear power, solar thermal power generation, hydrogen energy, chemical engineering, petrochemicals, aerospace, and other fields, possessing significant application potential. In this development context, this paper categorizes and summarizes recent research progress on the structural channel optimization and flow heat transfer characteristics of PCHE, analyzes related experimental and numerical simulation results, and finally, points out future research and development directions.

Keywords: Printed Circuit Heat Exchanger; Heat Transfer; Structure; Experiment; Simulation.

1. INTRODUCTION

As humanity continues to exploit and consume non-renewable resources like coal, natural gas, and oil, the continuous emission of greenhouse gases intensifies the problem of global climate change. To address this challenge that affects human living environments, it is essential to seek methods for energy conservation and emission reduction and develop new, more environmentally friendly energy solutions. Energy loss in the energy conversion and transmission process is a common issue, directly affecting energy utilization efficiency. In many industries, such as metallurgy, mechanical manufacturing, and oil extraction, the application of heat exchange equipment like evaporators, superheaters, and coolers is widespread. Optimizing the performance of these devices can not only enhance the safety and reliability of industrial equipment but also extend their service life and significantly reduce energy waste and environmental pollution [1-2].

From the working principle perspective, heat exchange equipment is mainly divided into three types: partitioned heat exchangers, mixed heat exchangers, and

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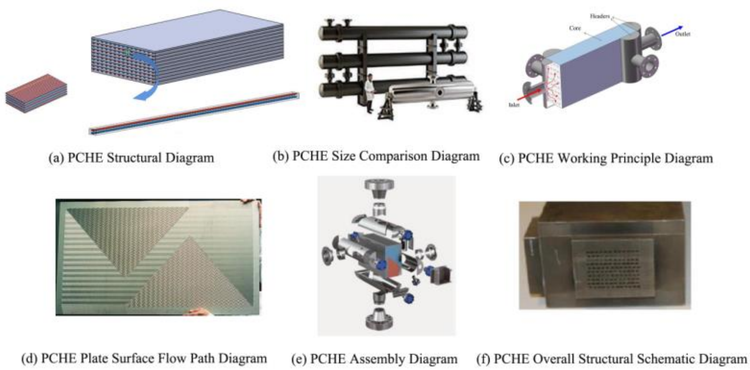
regenerative heat exchangers. Partitioned heat exchangers separate hot and cold fluids with a solid medium, mixed heat exchangers allow direct contact between hot and cold fluids, and regenerative heat exchangers use a periodic flow method to transfer heat through a heat storage body. Among these technologies, heat transfer enhancement techniques can be divided into active and passive methods. Active enhancement requires external energy input to improve efficiency, increasing system complexity and cost. In contrast, passive enhancement achieves this through optimized heat exchanger design without additional energy input. In practical applications, most heat exchangers use passive enhancement techniques. Heat transfer effects depend on various factors, including the convective heat transfer coefficient between the thermal fluid and the heat exchanger wall, the heat transfer coefficient of the cold fluid, and the thermal conductivity of the materials. As industrial technology develops, there is a growing demand for equipment miniaturization and lightweight. Heat exchangers can be divided into compact and non-compact types based on heat transfer surface density. Although traditional heat exchangers, such as shell-and-tube, plate-fin, and primary surface exchangers, are still widely used in some high-pressure and high-temperature environments, they often fail to meet all industrial needs. Therefore, PCHE, a new type of heat exchange device with efficient heat transfer performance, compact structure, and high temperature and pressure resistance, have become a research hotspot in recent years.

Research on PCHE mainly focuses on two aspects: one is the study of convective heat transfer coefficients in microchannels as a function of operating conditions and geometric parameters [3]; the other is the study of the relationship between resistance coefficients in microchannels and Reynolds numbers [4]. These studies aim to explore the flow and heat transfer laws under different conditions, providing theoretical guidance for the practical application of PCHEs. This article will summarize and categorize the experimental and simulation literature related to the structure of PCHEs and their internal flow and heat transfer characteristics over the past twenty years, and provide an outlook [5].

2. OVERVIEW OF THE STRUCTURAL DEVELOPMENT OF PCHE

Overview of PCHE Structural Development In 1985, PCHEs were successfully developed by the British company Heatric and put into production and manufacturing [6]. Although PCHEs have been developed for many years, to date, the complex flow and thermal characteristics caused by the coupling of temperature fields and flow fields in PCHEs have not been well studied. Therefore, a thorough understanding of their basic principles and performance characteristics is of significant importance.

PCHE represent a cutting-edge technology in the field of microchannel heat exchange, characterized by their resilience under low temperature and high pressure conditions, cost-effectiveness, compact size, tight structure, and superior heat transfer efficiency. These attributes make PCHEs highly promising for applications in concentrated solar power generation and nuclear reactions, among other areas. The manufacturing process of PCHE involves initially etching microchannels on the heat exchange plates using photoelectrochemical etching technology to serve as fluid pathways. Subsequently, the etched plates for hot and cold fluids are alternately stacked and fused into a unified whole using vacuum diffusion welding, forming the core of the PCHE heat exchanger. This assembled core is then encased within a specific container, where it is sealed through welding. The fluid channels typically have a semicircular cross-section of 1 to 2 mm, and the PCHE has a total surface area of 2500 m^2/m^3 per unit mass[7]. Compared to shell-and-tube heat exchangers, PCHEs offer significant advantages, such as requiring only 1/6 to 1/4 of the volume and mass for the same heat load and pressure drop, potentially saving up to 85% in space and substantially reducing the amount of steel used[8]. This simplifies structural design for platforms. Additionally, PCHEs can greatly minimize the risk of pressure drops and clogging, with a low risk of damage, thereby avoiding severe failures like shell bursts or leaks due to gasket failure[9]. Capable of operating under extreme conditions, PCHEs exhibit remarkable tolerance to low and high temperatures (ranging from -270°C to 900°C) and high pressure (up to 70 MPa), with heat exchange efficiencies reaching up to 98%[10].The schematic of the structure and assembly related to PCHEs shown in Figure 1.



(a) PCHE Structural Diagram (b) PCHE Size Comparison Diagram (c) PCHE Working Principle Diagram

(d) PCHE Plate Surface Flow Path Diagram (e) PCHE Assembly Diagram (f) PCHE Overall Structural Schematic Diagram

Figure 1 Typical PCHE diagram

Research on the PCHE structure commenced in the early 21st century, focusing mainly on two aspects: firstly, enhancing the flow and heat transfer performance of a certain PCHE by changing the material structure without altering the channel structure; and secondly, studying the impact of the PCHE's channel structure on its overall heat exchange performance to select the optimal channel parameters. This text summarizes and analyzes the structural development of PCHE from aspects of manufacturing processes, materials, stress analysis, and flow paths.

2.1 Research on PCHE Manufacturing Processes

The manufacturing of PCHE involves several key technologies, including precise etching of microchannels, material selection, and high-strength diffusion welding techniques. Rao et al. [11] discovered that the etching depth and corrosion factors of microchannels are significantly influenced by the etchant composition, temperature, and initial width of the opening, achieving the best channel quality with an etching solution of 10wt% $FeCl_3$, 10wt% HCl, and 5wt% HNO_3 at 40°C for an initial channel width of 190μm. Ma et al. [12] found that isotropy in the chemical etching process leads to inner rounded corners at the tail walls of wing-shaped fins in the actual etching process. The diffusion welding technique was used to connect the cold and hot side plates of the PCHE exchanger. Furthermore, the application of diffusion welding technology, especially the advanced diffusion bonding technique by Heatric Company in the UK, provided a solution for PCHE with interlayer-free, high-strength joints, further enhancing the overall performance and reliability of the heat exchanger.

2.2 Research on PCHE Plate Materials

Given the potential application of PCHEs in high-temperature, high-pressure environments, their plate materials must possess excellent mechanical strength, corrosion resistance, and long-term thermal stability. These properties not only directly affect the efficiency and reliability of the heat exchanger but also determine its lifespan in extreme conditions. Li et al. [13] compared Alloy800H, AlloyHX, Alloy230, Alloy617, concluding that Alloy617 is most suitable as the plate material for heat exchangers in high-temperature reactors. Mylavarapu et al. [14] designed a high-temperature helium gas test apparatus to test the heat transfer and pressure drop performance of PCHEs, with the design capable of reaching up to 900℃ and 3MPa. Under these high temperature and pressure conditions, suitable plate materials include Alloy617, Alloy230, Alloy800HT, AlloyHX, with Alloy617 being the most suitable due to its high allowable design stress, good thermal and physical properties, and stable microstructure.

2.3 Research on PCHE Structure and Stress

Due to its unique microchannel structure, the stress analysis of PCHEs is crucial for their heat transfer capabilities and overall performance efficiency. Lee et al. [15] analyzed the structure of a PCHE (made of SS316) focusing on the intermediate heat exchanger in a sodium-cooled fast reactor with supercritical CO_2 as the cooling medium. Temperature fields were obtained using FLUENT, and based on these, stress fields were derived using ANSYS Mechanical. Simulations were conducted for 2x1, 4x4, and 8x8 PCHE channel unit numbers. It was observed that the temperature field distribution for all three channel unit numbers remained essentially consistent. The highest stress occurred at the top of the channels, and the average stress on the PCHE channel walls was of a lower magnitude compared to the top of the channels, where stress increased rapidly. The pressure in the cold channels reached as high as 19.74MPa, hence the stress near the cold channels was greater than that near the hot channels. It was concluded that the stress distribution in PCHE channels is influenced by both pressure and temperature gradients. Yu et al. [16] noted that some stress results analyzed using analytical methods had large errors, hence they recommended using analytical methods to obtain the plate structure parameters first, followed by finite element method verification for heat exchanger design. Urquiza et al. [17] considered that transient stresses could sometimes far exceed the values predicted by steady-state analysis. Therefore, accurate analysis of thermal, hydraulic, and structural transient characteristics was necessary. The authors proposed a multiscale analysis with local volume averaging characteristics and a new effective porous medium method for PCHE simulation. This analysis could reveal structural flaws in the heat exchanger design process, minimizing thermal losses while maximizing flow uniformity, thermal efficiency, and mechanical strength. Yoon et al. [18] found through structural simulation that the optimal distance between channels on a single plate was 0.3mm.

2.4 Research on PCHE Flow and Flow Path

The flow patterns in PCHEs mainly include parallel flow, counterflow, and crossflow. Addressing these three flow patterns, Kim et al. [19] used numerical simulation methods to obtain the functional relationship between the average heat transfer coefficient of PCHEs under different flow patterns and their geometric parameters and material properties, providing an important reference for the design and manufacturing of PCHEs. PCHE flow paths have various cross-sectional shapes, with semicircular, rectangular, trapezoidal, and circular being the main ones used in engineering practice. Lee et al. [20] conducted a comparative study on the flow and heat transfer performance of these four cross-sectional shapes in Z-shaped channel PCHEs. The results showed that rectangular channel PCHEs had the best thermal performance but the worst hydraulic performance, while circular channels performed the worst thermally. After comprehensive analysis, semicircular channels were found to have the best thermo-hydraulic performance, hence semicircular cross-section shape PCHEs, as shown in Figure 2, have been widely used in actual engineering projects.

Figure 2 Semi-circular cross-section shape PCHE

In the classification of PCHE flow path types, Xu et al. [21] and Tsuzuki et al. [22] introduced the concepts of continuous and discontinuous flow paths. Continuous flow paths include straight channels [23], trapezoidal channels [24], serpentine channels [25], sinusoidal channels [26], and Z-shaped channels [27], while current discontinuous flow paths mainly consist of S-shaped channels and wing-shaped channels. In 2005, Tsuzuki et al. [28] first proposed the discontinuous S-shaped channel and conducted a series of studies using numerical simulation and experimental methods [29-30]. The results showed that S-shaped channel PCHEs could reduce the pressure drop to one-fifth of that of traditional Z-shaped PCHEs while maintaining comparable heat transfer capabilities. In 2008, Kim et al. [31] proposed arranging wing-shaped fins in PCHEs to increase the heat transfer area within the channels and conducted a numerical comparative study on the flow and heat transfer characteristics of wing-shaped PCHEs and traditional Z-shaped PCHEs. The results indicated that wing-shaped PCHEs maintained comparable heat exchange capabilities to traditional Z-shaped PCHEs while reducing the pressure drop to one-twentieth. With a variety of PCHE flow path types available, direct channel PCHEs, Z-shaped channel PCHEs, S-shaped fin PCHEs, and wing-shaped PCHEs are among the most common in engineering applications, as shown in Figures 1-4. Due to the complex internal flow in different operational conditions, understanding the flow and heat transfer mechanisms within each flow path type of PCHE under various conditions is crucial for their practical engineering application.

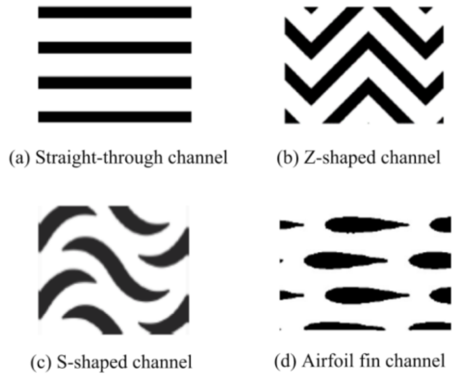


Figure 3 Schematic diagram of PCHE flow channels commonly used in four projects

3. NUMERICAL SIMULATION STUDIES

Due to the complexity of the PCHE channels, numerical simulation has always been a critically important research method for studying PCHE. Compared to experimental studies, numerical simulations offer more economical and convenient means, especially for investigating local flow and heat transfer states within different operating conditions of heat exchangers and for optimizing and improving internal parameters of the heat exchanger channels. Currently, numerical simulation studies on the flow and heat transfer characteristics of supercritical fluids are numerous, primarily focusing on S-CO_2 and helium as working fluids, with fewer studies on supercritical nitrogen. Hence, the following summary and simulation results will mainly address research related to S-CO_2 and helium as working fluids.

3.1 Numerical Simulation Studies on Straight Channel PCHEs

Aneesh et al. [32] developed a model of a straight channel PCHE with a semicircular cross-section, proposing its use as a heat exchanger for the International Thermonuclear Experimental Reactor (ITER). Using numerical simulations, the authors simulated the flow of helium within the PCHE, finding that the alignment and staggered arrangement of cold and hot channels had little impact on performance. Additionally, PCHEs with hemispherical dimples exhibited better performance. Chen et al. [33] studied the thermal steady-state performance of straight channel PCHEs through both experimental and numerical simulations. A dynamic model was created using commercial software to predict the steady and transient states of straight channel PCHEs, which was then compared with experimental results, confirming the applicability of the dynamic model in predicting experimental transient scenarios. Zhao et al. [34] investigated the flow of supercritical nitrogen in straight channel PCHEs through numerical simulation, discovering that the gasification efficiency of liquid nitrogen increased with inlet pressure. The model's calculation of the Fanning friction factor f had an error margin within ±15%, and the Nu number's error was within ±4%. Jeon et al. [35] used numerical simulations to study the flow and heat transfer of supercritical CO_2 in PCHEs. The PCHE utilized a heterogenous semicircular straight channel, finding that channel spacing almost did not affect the heat transfer performance of the PCHE, but had a significant impact on the structural reliability of the PCHE; the cross-sectional shape of the channel had no significant effect on heat transfer performance given an unchanged hydraulic diameter of the channel. Mylavarapu et al. [36] manufactured two PCHEs with straight channels to verify the feasibility of PCHEs in VHTRs, and through heat transfer correlations based on experimental data, numerical simulations showed reasonable accuracy in predicting the steady and transient behavior of straight channel PCHEs. Khalesi et al. [37] conducted a numerical simulation study on conjugate heat transfer and fluid flow analysis at the bottom plate wall of rectangular microchannels under the influence of uniform heat flux with supercritical CO_2, finding that the dramatic changes in specific heat affected heat transfer and flow along the channel, and wall shear stress and heat flux were increasing functions of working pressure; for high working pressures, the Nu number in laminar state was not affected by Re number.

3.2 Numerical Simulation Studies on Z-shaped Channel PCHEs

Meshram et al. [38] compared the flow and heat transfer performance of supercritical CO_2 in straight and Z-shaped channel PCHEs through numerical simulation methods. The study found that the overall heat transfer coefficient was related to the operational Reynolds number and channel diameter, with smaller diameters leading to higher heat transfer coefficients but also increased pressure drops; in Z-shaped channels, the overall heat transfer coefficient increased with bending angle and linearly decreased with pitch reduction. Although smaller heat exchangers result in lower expenditures, the increased pressure drop reduces the efficiency of the cycle, hence a comprehensive thermal analysis is necessary to achieve optimized operating conditions and heat exchanger sizes. Yoon et al. [39] developed two CFD models to study the thermo-hydraulic characteristics of fluid flow in Z-shaped channel PCHEs, establishing correlations of heat transfer performance and friction factor f with geometric parameters. In this study, CFD predictions were used to help develop correlations for the Nusselt number and friction factor f for laminar flow in semicircular tortuous channel PCHEs. The results indicated that the f in Z-shaped channels was mainly influenced by geometric shape, while the Nu number was affected by the overall heat exchanger design, including the compression section. CFD analysis with a dual-channel model helps predict the friction factor f, but depending on the design of the inlet and outlet plenums, it might overestimate or underestimate the thermal performance of serrated channel PCHEs. Wu et al. [40] analyzed the performance of different channel types of PCHEs in S-CO_2 Brayton cycles through numerical simulation, finding that Z-shaped channels had the highest heat exchange efficiency, 14% higher than straight channels, but with a ninefold increase in pressure drop. Yang et al. [41] studied the heat transfer and flow characteristics of straight and Z-shaped channels in PCHEs under S-CO_2 Brayton cycles using numerical simulation methods. It was found that the heat transfer capacity and flow pressure loss of Z-shaped channels were greater than those of straight channels, with the heat transfer capacity of Z-shaped channels being 24% higher than that of straight channels under the same conditions, and the flow pressure loss was more than double. Li et al. [42] explored the impact of structural parameters on the flow and heat transfer characteristics in serrated channel PCHEs using supercritical methane, finding that smaller channel diameters, pitch, and larger bending angles led to decreased flow performance but improved heat transfer performance.

3.3 Numerical Simulation Studies on Wing-shaped and S-shaped Channel PCHEs

Kim et al. [43] proposed a channel with wing-shaped fins and found that the pressure drop in channels with wing-shaped fins was only 1/20th of that in Z-shaped channels, while the heat transfer efficiency per unit volume remained essentially the same. Kim et al. [44] also used supercritical CO_2 as the working fluid to study the flow and heat transfer performance of PCHEs with wing-shaped fins. To assess the potential volume reduction of wing-shaped channel PCHEs, Pidaparti et al. [45] conducted an experimental study on the performance of PCHEs with discontinuous offset rectangular fins and NACA0020 wing-shaped fins, analyzing local heat transfer coefficients and friction factor f. The results indicated that wing-shaped channel PCHEs could reduce volume by 14.1% compared to serrated channel PCHEs under the same heat transfer efficiency. Cui et al. [46] conducted a numerical simulation study on the flow of supercritical CO_2 in PCHEs and designed two new structures based on existing wing-shaped structures to improve heat transfer performance. The findings showed that impingement and secondary recirculation at the leading edge of the fins could enhance the synergy of temperature gradients and velocity vectors, thus enhancing convective heat transfer; and that staggered arrangement and rational wing-shaped geometry could effectively reduce the influence of the boundary layer, improving flow and heat transfer performance. Chen et al. [47] used Z-shaped channels as a reference to compare the flow and heat transfer performance of CO_2 in different wing profile (NACA00XX) PCHEs, finding that as the thickness of the fins increased, heat transfer was enhanced, but considering both heat transfer and resistance performance, an increase in fin thickness led to decreased overall performance. Chu et al. [48] compared flat, elliptical, circular, wing-shaped, and improved wing-shaped channels through numerical simulation, finding that discontinuous fin structures could disturb the fluid more strongly, possessing a greater heat transfer capacity, and that the improved wing-shaped structure had the best heat transfer performance. Han et al. [49] used the surface response method and Computational Fluid Dynamics (CFD) to study the flow and heat transfer performance of silicon carbide PCHEs with Z-shaped and wing-shaped channels, analyzing performance based on the Fanning friction factor and Nusselt number in the cold fluid channels. The results showed that channel design significantly impacts the thermal efficiency and flow characteristics of PCHEs, especially the channel bending angle and diameter.

4. EXPERIMENTAL STUDIES

Due to the diverse shapes of PCHE channels and generally strong nonlinear turbulent flow of fluids, it's challenging to clarify internal rules through simple theoretical solutions. Therefore, experimental research has been a method of study for PCHEs across various countries, though due to the complexity of experimental systems, research on PCHEs remains limited. This section summarizes experimental results on the flow and heat transfer characteristics in PCHEs.

4.1 Experimental Studies on Straight Channel PCHEs

Chu et al. [50] conducted experiments with straight channel PCHEs in the context of a cooler in a supercritical CO_2 Brayton cycle. The experimental results showed that the heat transfer rate of supercritical CO_2 was 1.2 to 1.5 times higher than that of water under the same mass flow and inlet temperature conditions, and with the increase of

Reynolds number, the Nusselt number of supercritical CO_2 also increased, but the rate of increase was decreasing. Kruizenga et al. [51] studied the heat transfer and pressure drop characteristics of PCHEs under cooling conditions experimentally. Existing empirical correlations matched well with heat transfer characteristics far from the pseudo-critical point but predicted results were too high near the pseudo-critical point when using the fluid's average temperature. Using wall temperature significantly improved prediction accuracy, with frictional losses causing 80% of the total pressure drop and thermal acceleration effects causing 10% of the total pressure drop near the pseudo-critical point.

Liu et al. [52] studied the overall heat transfer coefficient U and Fanning friction factor f of straight channel PCHEs under typical operating conditions through experiments on heat transfer and flow characteristics, comparing them with classical criterion equations. The results showed that the criterion equations could well predict the heat transfer performance of PCHEs with an average deviation within 8.8% when Reynolds numbers ranged from 1400 to 4792. Yoo et al. [66] conducted experimental studies on propane condensation heat transfer and pressure drop performance in semi-circular straight channel PCHEs, proposing a heat transfer correlation similar to Akers et al. [67]. The study found that heat transfer coefficients and pressure drops increased with mass flow and vapor quality but decreased with increasing saturation pressure. The correlation was superior to existing studies like Boyko and Kruzhilin [68], with errors less than 15% across all data.

4.2 Experimental Studies on Z-shaped Channel PCHEs

Nikitin et al. [54] conducted an experimental study on a 3kW Z-shaped recuperator, with hot side CO_2 inlet temperatures and pressures of (280-300)°C and (2.2-3.2)MPa, and cold side CO_2 inlet temperatures and pressures of (90-108)°C and (6.5-10.5)MPa, finding the heat exchanger to be highly efficient and proposing empirical correlations based on overall experimental data. KAIST [55] developed a PCHE design program (KAIST_HXD) and built a supercritical CO_2 pressurization experimental setup (SCO2PE) to verify whether the designed Z-shaped PCHE met thermodynamic performance requirements. Li et al. [56] developed a new evaluation criterion based on Z-shaped PCHE experimental data, expressing it as the ratio of the average inlet and outlet temperatures to the pseudo-critical temperature, with performance improving as the ratio approached 1.

4.3 Experimental Studies on Wing-shaped and S-shaped Channel PCHEs

Kim et al. [60] conducted experimental analysis on a new form of PCHE inspired by the NACA0020 wing profile. Pidaparti et al. [61] conducted experiments on NACA0020 wing profile PCHEs and discontinuous rectangular rib PCHEs against the background of a supercritical CO_2 Brayton cycle, proposing empirical correlations based on local and average measured values. Ma et al. [62] studied the photochemical etching process of wing profile PCHEs experimentally, finding actual wing profiles had inverted rounded corners, and numerical simulations showed that real wing profiles could enhance heat transfer and increase pressure drop to some extent. Zhao et al. [63] studied the flow of supercritical nitrogen in PCHEs experimentally and through numerical simulations, comparing different mass flows and working pressures on PCHE flow and heat transfer performance, finding that pressure drop decreased and outlet temperature increased with increasing pressure at the same mass flow; and developed correlations for Nusselt numbers and friction factor f that better predicted the flow and heat transfer performance of supercritical nitrogen in wing profile PCHEs.

Chang et al. [64] conducted experiments on a newly proposed wing-shaped PCHE and analyzed the impact of thermal resistance changes near the pseudocritical point on heat transfer performance. They quantitatively evaluated the heat transfer performance using a dimensionless number—the ratio of bulk temperature to pseudocritical temperature. It was found that the heat transfer performance improved with an increase in average thermal resistance. Optimal heat transfer performance of the heat exchanger was achieved when the dimensionless number was around 1.03, at which point a corrected heat transfer correlation for dimensionless operating parameters was obtained near the pseudocritical point. Ngo et al. [65] conducted an experimental study using a Metal Printed Circuit Heat Exchanger (MCHE) with S-shaped fins, which maintained nearly the same heat transfer performance as traditional MCHEs with Z-shaped fins but with a 6-7 times reduction in pressure drop, confirmed through an S-CO_2 loop. Furthermore, empirical correlations for the pressure drop factor and Nusselt number for MCHEs with S-shaped fins were proposed. As illustrated in Figure 4, it is evident that, compared to MCHEs with S-shaped fins, MCHEs with Z-shaped fins exhibit better heat transfer performance but poorer flow characteristics.

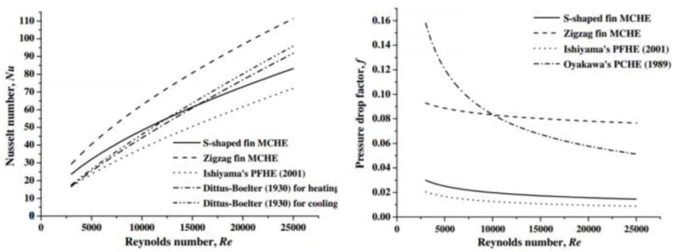


Figure 4 Changes of Nussel number and pressure drop factor with Reynolds number

5. CONCLUSION AND PERSPECTIVES

Due to its outstanding performance, PCHE have found widespread applications across various energy sectors. This article reviews the research progress on the structure and flow heat transfer characteristics of PCHEs over the past two decades. Based on the analysis above, future research should delve into the following areas:

(1) *Comprehensive and Unified Evaluation Standards or Performance Parameters for PCHEs*: In applications, a wide range of performance parameters for heat exchange equipment needs attention. The design optimization process often involves the coupling of multiple factors and variables, requiring the balancing and trading off of various performance parameters, making it difficult to compare different heat exchangers. Therefore, for compact heat exchangers like PCHEs, it is necessary to propose more comprehensive and unified evaluation standards or performance parameters. In addition to heat transfer and pressure loss, compactness should also be considered to more effectively quantify the comprehensive performance of PCHEs. This will aid in the structural design and optimization of PCHEs in various application fields.

(2) *Numerical Simulation Accuracy Improvement*: Numerical simulation is an important method for studying the heat transfer and flow characteristics of PCHEs,

offering advantages such as low cost, strong controllability of variables, and easy interpretation of results. However, for PCHE numerical simulations, research is needed on the selection of various models, treatment of near-wall areas, and changes in fluid thermophysical properties to improve the accuracy of numerical simulations. Moreover, although there are many empirical correlations for various flow channel structures, different heat carriers, and different operating conditions, they often apply to a narrow range of Reynolds numbers. There is a need for more accurate and universally applicable empirical correlations to provide references for the design and optimization of PCHEs.

These research directions aim to enhance the efficiency, reliability, and applicability of PCHEs in diverse energy applications, addressing both the design challenges and the need for accurate predictive tools to optimize performance and integration into energy systems.

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