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Research Progress on Printed Circuit Heat Exchangers (PCHEs)

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Abstract

The Printed Circuit Heat Exchanger (PCHE), an emerging microchannel compact heat exchanger, demonstrates significant application potential in cutting-edge fields such as supercritical carbon dioxide (S-CO_2) Brayton cycles, liquefied natural gas (LNG) processing, nuclear energy, and aerospace, owing to its exceptional compactness, high efficiency, and capability to withstand high pressures and temperatures. This review aims to systematically outline the research context, core findings, and existing controversies in PCHE technology, while also prospecting future research directions. Firstly, this paper introduces the fundamental structure, manufacturing process, and working principle of PCHEs. Subsequently, it provides a detailed review of major experimental and numerical simulation findings concerning their thermal-hydraulic characteristics under single-phase, two-phase, and supercritical conditions, with a focus on analyzing the performance optimization effects of channel geometries. Furthermore, it discusses key contentious points in current research, including the universality of correlations, the applicability of turbulence models, and performance uncertainties induced by manufacturing tolerances. Finally, based on current technological bottlenecks, future research is suggested to focus on intelligent multi-objective optimization design, the development of new materials and manufacturing processes, long-term reliability validation under extreme conditions, and artificial intelligence-based performance prediction and control.

Keywords

Printed Circuit Heat Exchanger (PCHE); Supercritical LNG; Compact Heat Exchanger; Heat Transfer Enhancement; Flow Resistance.

1. Introduction

With the increasing demand for higher efficiency, compactness, and lightweight design in industrial sectors such as energy, chemical processing, and aerospace, heat exchangers, as core components for energy exchange, face unprecedented challenges. Although traditional shell-and-tube heat exchangers are technologically mature, their low compactness and large volume limit their application in certain specialized scenarios. The Printed Circuit Heat Exchanger (PCHE), first pioneered by the UK's Heatric company in the 1980s, ingeniously adapts chemical etching and diffusion bonding technologies from printed circuit board (PCB) manufacturing, opening a new pathway for the development of high-performance compact heat exchangers[1].

The defining feature of the PCHE lies in its microchannel structure, typically with a hydraulic diameter less than 2 mm. This confers an exceptionally high surface area-to-volume ratio (reaching over 2500 m^2/m^3), far exceeding that of shell-and-tube heat exchangers (approx. 300 m^2/m^3) and even plate heat exchangers (approx. 200-1000 m^2/m^3)[2]. Furthermore, the diffusion bonding process results in a monolithic, robust core block without gaskets or braze materials, enabling it to withstand extreme pressures (up to 60 MPa and above) and temperatures (dependent on the parent material, up to 900°C or higher)[3]. These outstanding characteristics make it particularly suitable for applications involving extreme operating conditions and space constraints, such as:

Supercritical Carbon Dioxide (S-CO_2) Power Cycles: S-CO_2 exhibits drastic property variations near its critical point, and the cycle operates at very high pressures (20-30 MPa). PCHEs are ideal for recuperators and coolers, crucial for enhancing overall cycle efficiency.

Liquefied Natural Gas (LNG): Used as main cryogenic heat exchangers, handling ultra-low temperature mixed refrigerants.

Generation IV Nuclear Reactors: Such as molten salt reactors and sodium-cooled fast reactors, requiring heat exchangers to operate reliably under high temperature, high pressure, and intense radiation environments.

Fuel Cell Systems: Used for fuel reforming and waste heat recovery.

Aerospace: Used for recuperators in gas turbines and onboard environmental control systems.

Given the importance of PCHEs, numerous studies have been conducted by researchers worldwide. This review will systematically outline the development within this field, summarize key research findings, analyze existing controversies, and prospect future research directions, aiming to provide a reference for researchers and engineers in related fields.

2. Structure, and Working Principle of PCHEs

2.1. Basic Structure

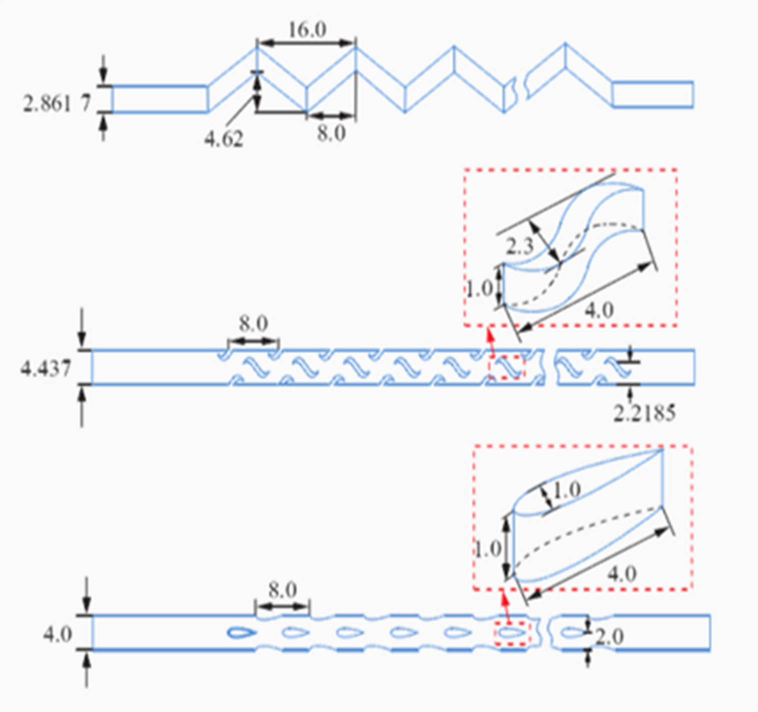

Figure 1. Types of channel structures

PCHE cores are fabricated by chemically etching fluid flow passages into flat metal plates. These etched plates are then stacked alternately for hot and cold streams and bonded together under high temperature and pressure in a diffusion bonding furnace, forming a solid, leak-proof block.

After diffusion bonding, the channels for the hot and cold fluids are securely separated, exchanging heat solely through the solid metal walls. The most basic channel form is straight; however, its heat transfer performance is not optimal. To enhance heat transfer, researchers have developed various complex channel configurations, such as:

Zigzag Channels: Periodically alter the flow direction, disrupting the hydrodynamic boundary layer and enhancing heat transfer, but significantly increasing pressure drop.

Sinuous Channels: Offer smoother flow compared to zigzag channels, achieving a better balance between heat transfer enhancement and pressure drop reduction.

Airfoil-shaped Channels: Designed based on the shape of aircraft wings, they effectively guide the fluid, reducing flow separation and vortex generation, thereby achieving efficient heat transfer with low resistance.

2.2. Working Principle

As a recuperative (indirect-contact) heat exchanger, the PCHE operates on the fundamental laws of heat transfer. Hot and cold fluids flow within their respective micro channels, and heat is transferred from the high-temperature fluid to the low-temperature fluid through the solid walls. Due to its microchannel characteristics, flow is typically in the laminar or transitional regime (Reynolds number Re usually between 1000-3000), where inertial and viscous forces are comparable. Consequently, the heat transfer and flow characteristics differ significantly from those in conventional channels.

3. Research Development and Key Findings

The research history of PCHEs can be broadly divided into three stages: the fundamental exploration stage (focusing on characteristics of basic straight and zigzag channels), the performance optimization stage (developing new channel configurations and multi-objective optimization), and the system application stage (focusing on specific working fluids and integration into actual systems).

3.1. Single-Phase Flow and Heat Transfer Characteristics

Early research focused on the single-phase flow and heat transfer characteristics of fluids like water and helium in PCHEs, aiming to establish basic correlations for friction factor (f) and Nusselt number (Nu).

Tatsuki et al. [4] conducted experimental studies on PCHEs with zigzag channels. They found that the continuous turning effect induces secondary flows and flow separation even at relatively low Re numbers ($Re < 1000$), significantly enhancing heat transfer, but also resulting in friction factors several times higher than those in conventional straight channels. Their experimental data provided an important validation benchmark for subsequent numerical simulation studies.

With advancements in Computational Fluid Dynamics (CFD) technology, numerical simulation has become a powerful tool for investigating the complex internal flow and heat transfer details of PCHEs. Nikitin et al. [5] conducted detailed experimental and numerical studies on the heat transfer and pressure drop characteristics of S-CO_2 in straight-channel PCHEs. They found that near the critical region, the specific heat capacity (Cp) of S-CO_2 peaks, leading to anomalous heat transfer enhancement, with Nusselt numbers far exceeding predictions from traditional correlations. Their research emphasized the importance of accounting for drastic property variations under supercritical conditions and proposed modified correlations applicable to S-CO_2.

To find the optimal balance between heat transfer enhancement and pressure drop penalty, researchers began exploring bio-inspired and other high-efficiency channel structures. Ma et al. [6] systematically compared the performance of straight, zigzag, and airfoil-shaped channels using numerical simulations. They employed the Performance Evaluation Criterion (PEC) to assess overall performance. Results indicated that airfoil channels provide the highest heat transfer coefficient under identical pumping power consumption, with PEC values significantly higher than traditional zigzag channels, offering a new direction for PCHE channel design.

3.2. Two-Phase Flow and Supercritical Fluid Applications

PCHE applications in LNG and refrigeration systems involve two-phase flow, while S-CO_2 cycles involve supercritical fluids. The properties of these fluids change drastically near the phase transition point or critical point, leading to complex behavior.

For two-phase flow, research focuses on flow pattern maps, pressure drop characteristics, and heat transfer coefficients during flow boiling and condensation. Due to the micro-scale channels, surface tension effects are enhanced, with bubbly and slug flows being dominant regimes. The occurrence of dryout also differs from conventional channels. Research data in this area is relatively scarce, and a widely accepted universal predictive model has yet to be established.

For supercritical S-CO_2, as mentioned earlier, the work of Nikitin [5] and Kruizenga et al. [7] shows that traditional correlations like Dittus-Boelter cannot accurately predict heat transfer behavior near the critical region. Heat transfer deterioration is sometimes observed, related to the interaction of buoyancy and thermal acceleration effects. Therefore, developing CFD models and engineering correlations that accurately capture the variable property effects of S-CO_2 is a current research hotspot.

3.3. Materials, Manufacturing, and Long-Term Reliability

The performance and longevity of PCHEs depend heavily on their materials and manufacturing processes. For high-temperature applications (e.g., nuclear energy), nickel-based alloys (such as Inconel 617, Hastelloy X) are preferred materials. Mylavarapu et al. [8] investigated the mechanical properties and diffusion bonding quality of PCHEs intended for high-temperature gas-cooled reactors. Through microstructural analysis and mechanical testing, they demonstrated that high-quality diffusion bonded joints can possess strength comparable to the base metal. However, long-term service at high temperatures raises concerns regarding material creep, fatigue, and potential environmental corrosion effects. Minor defects during manufacturing, such as slight deviations in channel dimensions or incomplete bonding, can significantly impact the final heat transfer performance and mechanical strength.

4. Existing Controversies and Challenges

Despite significant progress in PCHE research, controversies and challenges persist.

Universality of Heat Transfer and Flow Resistance Correlations: Numerous published correlations for f and Nu are mostly based on specific channel shapes, specific working fluids, and specific Re number ranges. Given the diversity of PCHE channel geometries, finding a universal correlation is challenging. For instance, correlations for zigzag channels are entirely unsuitable for predicting the performance of airfoil-shaped channels. This leads to heavy reliance on time-consuming CFD simulations or expensive experiments when designing PCHEs with new architectures.

Accuracy of CFD Simulations and Turbulence Model Selection: For the laminar and transitional flows common in PCHEs, standard turbulence models like k-ε exhibit poor predictive accuracy. Although low-Re number models (e.g., low-Re k-ω SST) or Direct Numerical Simulation (DNS) can provide more accurate results, they require (extremely high) computational resources. When simulating S-CO_2, accurately handling variable properties and effects like buoyancy and thermal acceleration remains a challenge for CFD.

Uncertainty Due to Manufacturing Tolerances: Ideal CFD models assume perfect channel dimensions. However, the etching and diffusion bonding processes introduce micron-level dimensional deviations and surface roughness. How these minor manufacturing tolerances affect actual flow and heat transfer performance lacks systematic study, leading to a gap between theoretical design and actual product performance.

Performance and Reliability at Cryogenic and High Temperatures: In cryogenic applications like LNG, thermal contraction stresses and low-temperature embrittlement of materials require consideration. In high-temperature applications, the mechanisms of creep-fatigue interaction, oxidation, and performance degradation under long-term service are not fully understood, lacking sufficient long-term experimental data for support.

5. Future Research Directions

Based on the current research status and challenges, future research directions can be summarized as follows:

Intelligent Design and Multi-Objective Optimization: Utilize artificial intelligence techniques such as machine learning and genetic algorithms for the automated optimal design of PCHE channel topology (e.g., non-uniform distribution, multi-scale structures), shape, and dimensions, aiming to simultaneously maximize heat transfer efficiency, minimize pressure drop, and enhance structural strength. Develop automated design platforms integrating CFD and optimization algorithms.

Exploration of New Materials and Processes: Develop new alloys and ceramic matrix composites suitable for more extreme environments (e.g., higher temperatures, stronger corrosivity). Explore the potential of additive manufacturing (3D printing) for fabricating PCHEs, to overcome limitations imposed by traditional etching processes and enable more complex and efficient three-dimensional flow channel structures.

Long-Term Experimental Validation under Extreme Conditions: Conduct long-term service experiments with special working fluids like S-CO_2, liquid metals, and molten salts. Systematically study the performance evolution and failure mechanisms of PCHEs under the coupled effects of thermal-mechanical-chemical fields, providing a solid data foundation for engineering design and safety standard establishment.

Advanced Measurement Techniques and High-Fidelity Simulation: Apply advanced optical measurement techniques such as micro-PIV (Particle Image Velocimetry) and LIF (Laser-Induced Fluorescence) for non-invasive visualization and measurement of flow and temperature fields within PCHE micro channels, for validating and improving CFD models. Develop numerical methods with higher accuracy and lower computational cost.

System Integration and Control Strategies: Investigate the dynamic response characteristics, control strategies, and coupling laws with other components of PCHEs within complete energy systems (e.g., S-CO_2 power plants), ensuring the efficient and stable operation of the entire system.

6. Conclusion

The Printed Circuit Heat Exchanger (PCHE), a significant innovation in the field of compact heat exchangers, has become a critical component for next-generation high-efficiency energy systems due to its unparalleled compactness, pressure resistance, and temperature tolerance. After decades of development, research has progressed from characterizing basic channels to multi-objective optimization of complex geometries and in-depth exploration of specific applications. Through experimental and simulation methods, researchers have largely elucidated the flow and heat transfer mechanisms of traditional structures like straight and zigzag channels, and innovatively proposed low-resistance, high-efficiency bio-inspired channels like the airfoil shape.

However, the technology still faces challenges such as the lack of universal correlations, insufficient CFD simulation accuracy, uncertainty regarding the impact of manufacturing tolerances, and a scarcity of long-term reliability data. Future research should focus on intelligent design methods integrating artificial intelligence, pioneering new materials and processes, accumulating long-term experimental data under extreme conditions, and developing advanced measurement and simulation techniques. By addressing these challenges, the performance and application boundaries of PCHEs will be further expanded, contributing significantly to the innovation and decarbonization of global energy technology.

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