

A Study on Flow and Heat Transfer Characteristics in Printed Circuit Heat Exchangers with Zigzag Channels through PIV and CFD Analysis

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Extended Abstract

Printed circuit heat exchangers (PCHEs) are fabricated by creating microchannels in thin metal plates using chemical etching. These plates are then stacked and joined via diffusion bonding, a process involving high pressure at temperatures below the melting point. The internal microchannels provide a significantly larger heat transfer area per unit volume compared to conventional heat exchangers, enabling miniaturization and lightweight designs. Unlike traditional heat exchangers, which require welding at their joint areas, PCHEs can be manufactured as monolithic structures, offering superior mechanical strength and operation across extremely wide temperature and pressure ranges. These advantages have recently expanded PCHE applications to various energy and industrial sectors, including hydrogen refueling stations, LNG carriers, and supercritical carbon dioxide (sCO₂) power generation systems. Particularly, as thermal management demands in each industry become increasingly complex and critical, the potential for PCHE utilization continues to grow.

Numerous studies have explored various channel geometries to enhance PCHE thermal-hydraulic performance. Among these, the zigzag channel is the most widely investigated due to its high heat transfer performance per unit volume. While zigzag channels typically exhibit a higher pressure drop compared to other configurations due to abrupt changes in flow direction, the vortex generation at the bends promotes turbulence, thereby significantly improving heat transfer.

Many researchers have analyzed the influence of zigzag channel bend angles on fluid flow and heat transfer characteristics. Prior studies [1-5] primarily focused on the thermal-hydraulic performance of zigzag channels within limited flow regimes, utilizing sCO₂ and helium as working fluids. These working fluids are commonly employed in advanced reactor systems such as Brayton cycle systems and High-Temperature Gas-cooled Reactors. In contrast, most operating or developing nuclear power systems, including small modular reactors (SMRs), predominantly use water as the working fluid in both primary and secondary loops. Furthermore, some water-based systems, like research reactors, operate under relatively low thermal power, low flow rates, and intermediate temperature conditions. However, existing research largely concentrates on the turbulent flow regime, leaving a notable lack of studies on thermal-hydraulic performance and correlations for water as a working fluid in the laminar and transitional flow regimes, particularly at Reynolds numbers below 2500. Therefore, investigating the thermal-hydraulic performance of zigzag channels under these low Reynolds number, water-based conditions is crucial.

Accordingly, this study experimentally analyzed the flow patterns inside a zigzag channel, using water as the working fluid under various Reynolds number conditions, through particle image velocimetry (PIV) flow visualization. Based on the acquired experimental data, CFD simulations were validated. Subsequently, the flow characteristics and heat transfer performance for various bend angles were numerically analyzed. Building on this, through performance factor evaluation, the optimal bend angle that maximizes thermal-hydraulic performance was derived. Additionally, new correlations for friction factor and Nusselt number, critical parameters for PCHE design, are proposed.

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References

- [1] S. Baik, S.G. Kim, J. Lee, and J.I. Lee, "Study on CO₂–water printed circuit heat exchanger performance operating under various CO₂ phases for S-CO₂ power cycle application," *Applied Thermal Engineering*, vol. 113, pp. 1536-1546, 2017.
- [2] Z. Zheng, D.F. Fletcher, and B.S. Haynes, "Transient laminar heat transfer simulations in periodic zigzag channels," *International Journal of Heat and Mass Transfer*, vol. 71, pp.758-768, 2014.
- [3] S.-h. Liu, R.-l. Liu, Y.-p. Huang, X.-l. Zhu, L. Yang, J. Tang, B. Han, T.-y. Xing, and X.-b. Zhao, "Experimental study on flow and heat transfer of supercritical carbon dioxide in zigzag channels with bending angle 30° for advanced nuclear systems," *Annals of Nuclear Energy*, vol. 185, 109720, 2023.
- [4] M. Saeed, A.S. Berrouk, M.S. Siddiqui, and A.A. Awais, "Numerical investigation of thermal and hydraulic characteristics of sCO₂-water printed circuit heat exchangers with zigzag channels," *Energy conversion and management*, vol. 224, 113375, 2020.
- [5] A. Meshram, A.K. Jaiswal, S.D. Khivsara, J.D. Ortega, C. Ho, R. Bapat, and P. Dutta, "Modeling and analysis of a printed circuit heat exchanger for supercritical CO₂ power cycle applications," *Applied Thermal Engineering*, vol. 109, pp. 861-870, 2016.