A study on the thermal–hydraulic characteristics of zigzag channel PCHE using PIV experiment and CFD

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1. Introduction

Printed Circuit Heat Exchangers (PCHEs) are manufactured by forming microchannels in thin metal plates through a chemical etching process, and then pressurizing them at high temperatures below their melting points through a diffusion bonding process. Due to the presence of internal microchannels, PCHEs provide a high heat transfer surface area per unit volume, enabling compact and lightweight designs. Additionally, unlike traditional welded heat exchangers, PCHEs have no joints, resulting in superior mechanical strength. These advantages have led to their widespread adoption as next-generation heat exchangers in various industrial applications, including high-temperature gas reactors (HTRs) and small modular reactors (SMRs).

To enhance the thermal–hydraulic performance of PCHEs, various channel configurations have been investigated [1,2]. Notable examples include straight, zigzag, and airfoil channels, among which the zigzag channel has been the most extensively studied due to its high heat transfer performance per unit volume. Zigzag channels have a higher pressure drop than other configurations because of the abrupt change in flow direction. However, the eddy effect generated at the bend enhances turbulence, improving heat transfer performance. Previous studies [3,4] have analyzed the thermal–hydraulic performance of zigzag channels with different bending angles, but most research has focused on turbulent regimes using helium or supercritical carbon dioxide loops.

In this study, the internal flow patterns and characteristics of zigzag channels were experimentally analyzed using particle image velocimetry (PIV) visualization with water as the working fluid. Based on these experimental findings, numerical methodologies were validated, and the optimal bending angle of zigzag channels was investigated in laminar and transitional flow regimes.

2. Research method

2.1 Experimental method

Fig. 1 shows the experimental loop and visualization system. The PIV system consists of a light source, tracer particles, and a high-speed camera. To illuminate the test section, a continuous-wave laser with a maximum output of 8.44W was used to generate a 532 nm wavelength laser sheet beam. Fluorescent particles were introduced to visualize the flow inside the zigzag channel. The captured images were processed using Dynamic Studio software to perform PIV analysis, enabling the qualitative evaluation of internal flow patterns. Additionally, differential pressure transmitters and thermocouples were installed at the inlet and outlet of the test section to measure pressure drop and temperature, facilitating the analysis of flow characteristics.

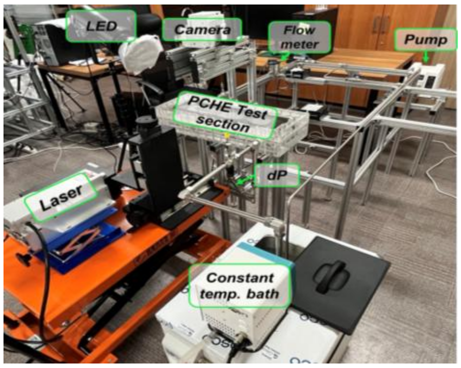

Fig. 1 Experimental loop and visualization setup.

2.2 Numerical method

In this study, the thermal–hydraulic characteristics of a zigzag channel were numerically analyzed using the commercial software ANSYS Fluent 18.1. The simulations were conducted under 3D, steady-state, and incompressible flow conditions, employing the SST k-ω turbulence model. This model applies the k-ω model near walls to accurately capture boundary layer behavior, and the k-ε model in the free stream to improve overall flow prediction. Due to these advantages, it is widely applied in the flow analysis of PCHEs with complex internal geometries [5,6]. The Reynolds number within the channel was set between 300 and 2,500, and water at 30°C was used as the working fluid. Fig. 2 shows the mesh structure used for numerical analysis. To optimize computational efficiency, a unit structure model was selected, with the channel diameter and height fixed at 3mm and 1mm, respectively, while the bending angle was varied between 10° and 40°. Fig. 3(a) illustrates the results of the grid-independence test, where it was observed that when the number of mesh elements exceeded approximately 10,000,000, further increases had a negligible impact on the simulation results. Therefore, this number of grids was chosen to balance accuracy and computational cost. Fig. 3(b) is a validation graph comparing the pressure drop between the experimental results and CFD simulations. The pressure drop predicted by CFD exhibited an error margin within approximately 10% when compared with experimental results, indicating a reasonable level of agreement. Based on this validated numerical approach, further analyses were conducted to investigate the thermal–hydraulic characteristics of the channel while varying the bending angle.

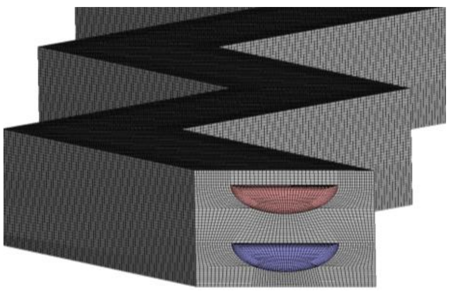

Fig. 2 The mesh structure used for numerical analysis.

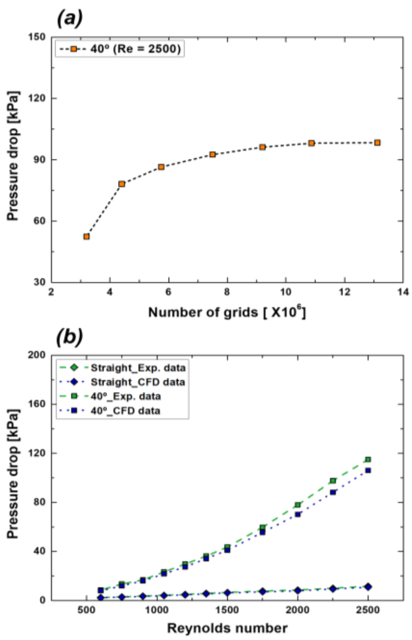

Fig. 3 (a) the results of the grid-independence test; (b) CFD validation results compared with experimental results.

3. Results

3.1 Comparison of flow patterns between PIV and CFD

To analyze the flow characteristics under various Reynolds numbers in the 40° zigzag channel, the PIV experimental results were compared with CFD simulations. Factors such as fluid property changes due to temperature variations and limitations in equipment resolution can lead to an overestimation of discrepancies between experimental and numerical results when directly comparing raw data without normalization. Therefore, in this study, the relative vorticity-z ratio was utilized to normalize the flow characteristics before comparison.

Fig. 4 presents the PIV images and CFD relative vorticity-z ratio results at Reynolds numbers of 600 and 2500. As the Reynolds number increases, the recirculation zone becomes stronger and more distinct, while the size and intensity of vortices inside the channel increase, further enhancing the turbulence effect within the channel.

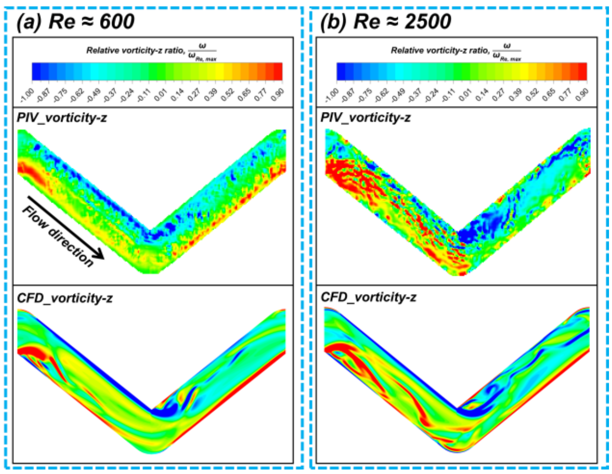

Fig. 4 Relative vorticity-z ratio images of PIV and CFD.

3.2 Thermal-hydraulic performance according to the bend angle of the zigzag channel.

Fig. 5(a) illustrates the pressure drop in zigzag channels with various bending angles. The results show that as the bending angle increases, fluid resistance also rises, leading to a greater pressure drop. In particular, the 40° zigzag channel exhibited the highest pressure drop, which can be attributed to the increased flow complexity caused by abrupt directional changes.

Fig. 5(b) presents the average heat transfer rate as a function of the bending angle. Similar to the pressure drop trend, the average heat transfer rate increases as the bending angle and Reynolds number increase. This result suggests that while abrupt flow direction changes lead to higher pressure drop, they also promote fluid mixing, thereby enhancing heat transfer performance.

These findings indicate that an increase in pressure drop enhances heat transfer performance, whereas a decrease in pressure drop results in reduced heat transfer efficiency. Therefore, to comprehensively evaluate these opposing effects, the thermal performance factor (η) is introduced, which is essential for determining the optimal bending angle in PCHE. The thermal performance factor is calculated using equation (1):

$$\eta = \frac{\left(Nu_\alpha / Nu_{straight}\right)}{\left(f_\alpha / f_{straight}\right)^{1/3}} \qquad (1)$$

Fig. 6 illustrates the thermal performance factor of zigzag channels with different bending angles under various Reynolds number conditions. In the Reynolds number range of 300–900, the 40° zigzag channel exhibited the highest thermal performance factor, showing a general trend of increasing thermal performance with increasing bending angle. This phenomenon occurs because, in the low Reynolds number region, the pressure loss difference caused by variations in the bending angle is relatively small, resulting in a limited effect on the thermal performance factor. However, as the Reynolds number increases to the range of 1,200–2,500, the 20° zigzag channel demonstrated the highest thermal performance factor. This can be attributed to the fact that in the 30° and 40° zigzag channels, the vortices generated at the channel bends intensify significantly with increasing Reynolds number, leading to a substantial rise in pressure drop.

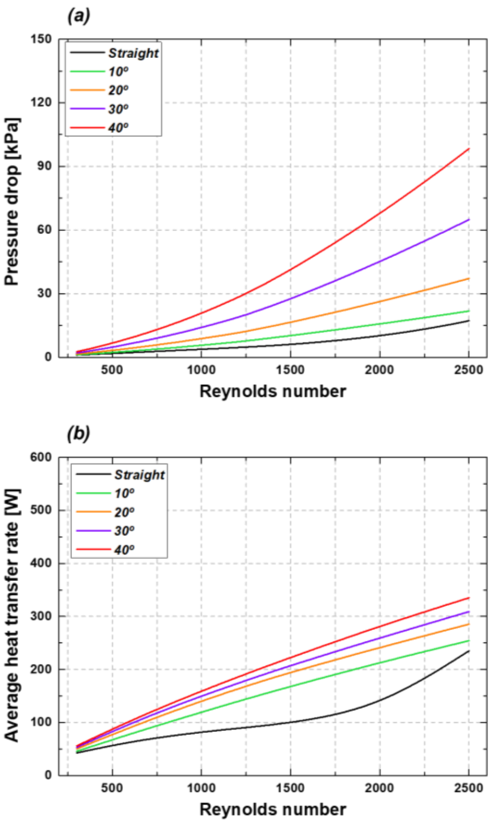

Fig. 5 (a) the pressure drop; (b) average heat transfer rate in zigzag channels with various bending angles.

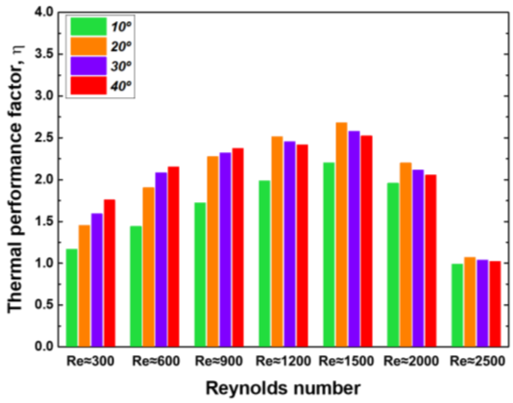

Fig. 6 The thermal performance factor of zigzag channels with different bending angles under various Reynolds numbers.

4. Conclusions

In this study, the thermal-hydraulic characteristics of zigzag channels with various bending angles were analyzed through both experimental and numerical approaches. To ensure the reliability of the numerical analysis, a comparison between the simulated and experimental pressure drop results showed an accuracy within 10%. The PIV visualization technique was employed to compare flow characteristics with CFD results, confirming similar flow patterns between experiments and simulations using relative vorticity-z ratio. For Reynolds numbers in the range of 300–900, the 40° zigzag channel exhibited the highest thermal performance factor. This is because, at low Reynolds numbers, the difference in pressure drop due to variations in the bending angle is relatively small, resulting in a limited impact on the thermal performance factor. However, in the range of 1,200–2,500, the 20° zigzag channel showed a sharp increase in the thermal performance factor, confirming it as the optimal design among all tested channels. This can be attributed to the fact that, in the high Reynolds number region, larger bending angles cause an exponential increase in pressure drop, which outweighs the benefits of enhanced heat transfer performance, thereby significantly affecting the overall thermal performance factor.

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