Thermal-hydraulic performance analysis of zigzag channel PCHE according to bending angle

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1. Introduction

Printed Circuit Heat Exchanger (PCHE) is manufactured through various process. First chemical etching method is commonly used to make microchannels from thin metal plates. Then stacking them and applying high pressure at high temperature through a diffusion bonding method. The microchannels allow for a larger heat transfer area per unit volume compared to conventional heat exchangers, resulting in compactness and weight reduction. Moreover, due to being manufactured as a single module, it demonstrates exceptional mechanical strength, allowing for operation in extreme environments. As a result of these advantages, it is a next-generation heat exchanger used in various industrial applications such as High Temperature Reactors (HTRs) and Small Modular Reactors (SMRs).

Numerous studies have been conducted to enhance the thermal-hydraulic performance of PCHE[1,2] by applying various shape of channels (e.g. straight, zigzag, airfoil etc.). Especially the zigzag channels were studied a lot compared to other channel shape owing to its high heat transfer performance per unit volume. Although zigzag channel of PCHE induces higher pressure drop compared to other channel shape due to abrupt flow direction changes, the vortices generated at the bend points enhance turbulent flow effects, resulting in superior heat transfer performance. Many previous studies [3,4] have investigated the thermal-hydraulic performance of zigzag channels based on various angles, but these studies have mainly focused on high Reynolds number using gas-to-gas loop. In this study, we investigate the optimal bend angle of zigzag channels for low Reynolds numbers with a water-to-water loop and analyze the Reynolds number variation. Based on the results of the research, we propose a new correlation to accurately predict the thermal-hydraulic performance of PCHE which embedding zigzag channels with water to water loop .

2. Numerical method

In this study, only the core part of the PCHE was considered, as the header part demonstrates relatively lower pressure drop and heat transfer performance compared to the core part. Fig. 1 shows the numerical-model and parameters of the PCHE. The analysis time was reduced through periodic boundary conditions on the top, bottom, left, and right sides of a unit structure. The channel diameter (D) was set to 1.5mm, height (H) to 0.5mm, and channel wall thickness (t) to 1mm.

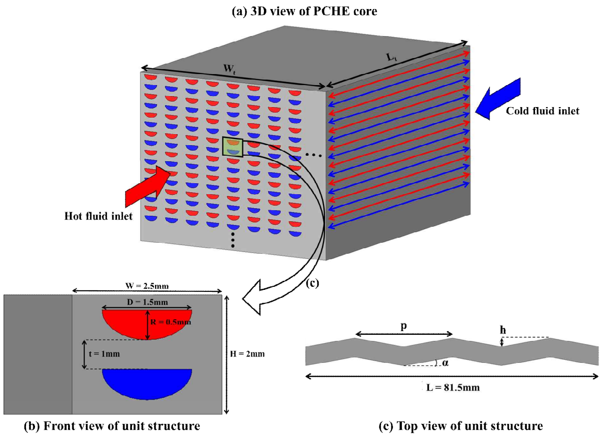

Fig. 1 Schematic of the PCHE numerical-model according to bend angles : (a) 3D view of PCHE core, (b) front view and (c) top view of unit structure.

Table I: Geometric variables of the zigzag channel.

	α (°)	p (mm)	h (mm)
Geometric variables	10	12.93	1.14
	20	12.09	2.2
	30	10.95	3.16
	40	9.53	4

Additionally, the bend angle of the zigzag channels (α) was varied from 10 to 40 degrees at intervals of 10 degrees, and the length of the PCHE (L) was set to 81.5mm. The detailed specifications are listed in Table I.

The analysis was conducted using ANSYS Fluent 18.1 under 3D steady-state conditions. The Reynolds number ranges are from the laminar to transition flow regime. In addition, considering the potential transition from laminar to turbulent flow due to the curved shape of the zigzag channels, the Transition SST model was applied. The inlet temperatures of the hot channel and the cold channel were set to 80°C and 20°C, respectively. Since fluid properties depend on temperature, they were selected by referencing the NIST Chemistry database. Fig. 2 shows the meshing and grid independency test results of the analysis model. Through grid independency test, it was confirmed that the variation in analysis results was negligible when the number of grids exceeded 3,490,000. Therefore, considering the analysis time, approximately 3,490,000 grids were used for the analysis.

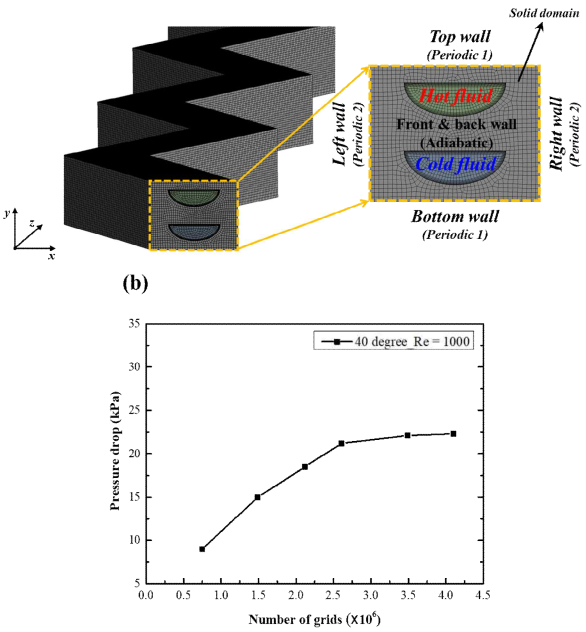

Fig. 2 Grid independence test for the 40-degree zigzag model: (a) meshing of the numerical model, (b) the plot of pressure drop according to the number of grids.

3. Results

3.1 The thermal-hydraulic performance according to the bend angle of the zigzag channel.

In this study, the effect of the bend angle of the zigzag channel on the thermal-hydraulic performance was analyzed. As the channel bend angle increased, the flow resistance affecting the fluid increased. In this regard, as shown in Fig. 3, the highest pressure drop occurred in the 40-degree zigzag channel, attributed to the increased flow separation and complex flow patterns due to the rapid change in flow direction with increasing channel bend angle. At all bend angles, an increase in Reynolds number led to an increase in pressure drop. In the case of the 40-degree zigzag channel, the maximum pressure drop was observed to be up to 7.83 folds higher compared to the 10-degree zigzag channel.

Fig. 4 shows the heat transfer rate according to the bend angle of the zigzag channel. The heat transfer rate demonstrates a tendency to increase as the bend angle increases. This is analyzed to be due to a significant increase in the intensity of vortices generated at the bend points as the bend angle increases, promoting fluid mixing and consequently enhancing heat transfer rate. The heat transfer rate of the 40-degree zigzag channel is up to 1.54 times higher compared to the 10-degree channel.

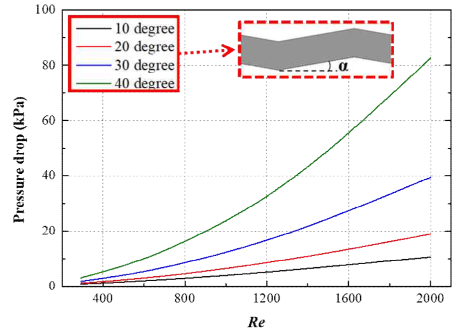

Fig. 3 Variation of pressure drop with Reynolds number.

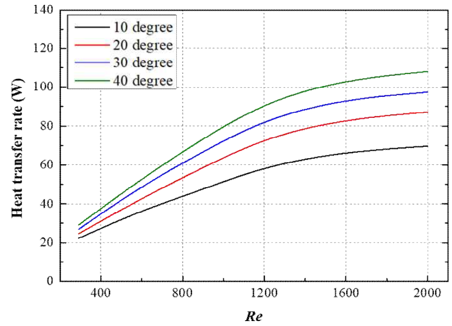

Fig. 4 Variation of heat transfer rate with Reynolds number.

3.2 Comprehensive performance factor according to the bend angle of the zigzag channel.

Generally, the heat transfer performance of zigzag channels increases concurrently with the rise in pressure drop. This phenomenon can be attributed to the bend points of the zigzag channel, which disrupt the flow and effectively promote mixing. Therefore, it is important to evaluate heat transfer performance and pressure drop simultaneously through comprehensive performance metrics. The comprehensive performance factor is as follows:

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

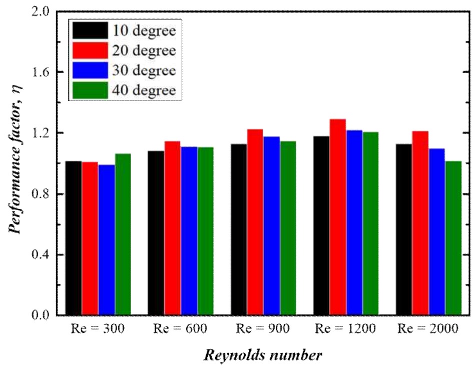

Fig. 5 Performance factor of all zigzag models at different Reynolds numbers

Fig. 5 shows the comprehensive performance factor according to the bend angle of the zigzag channel. In the range of Reynolds numbers from 600 to 1200, the comprehensive performance factor shows the highest values for the 20-degree zigzag channel. Fig. 6 shows the pathlines of the zigzag channel at a Reynolds number of 900. In Fig. 6(c) and (d), at bend angles of 30 and 40 degrees, flow separation occurs due to abrupt shape changes at the bends, resulting in the formation of high-intensity vortices. However, for a bend angle of 20-degree, no vortices are formed due to the absence of flow separation, leading to the highest heat transfer performance relative to pressure drop.

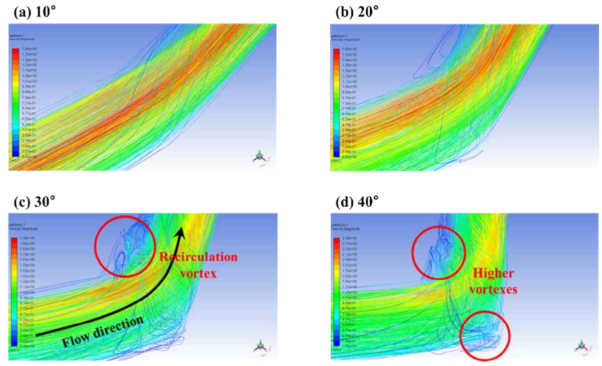

Fig. 6 Comparison of velocity pathlines with Re = 900 according to bending angle.

3.3 Development of CFD correlations.

In this study, we analyzed the key design parameters, namely the friction factor and Nusselt number, in the fabrication of PCHE. To analyze the impact of these design parameters according to the bend angle of the zigzag channels, we evaluated the thermal-hydraulic performance at various bend angles. For this purpose, extensive data was obtained through CFD simulations. The correlation for the Nusselt number was formulated with Reynolds number, bend angle, and Prandtl number as independent variables, while the friction factor was formulated with Reynolds number and bend angle as independent variables, respectively. We utilized multiple regression analysis to generalize the relationships between various independent variables and dependent variables, presenting the following correlations:

$$f = 29.1955 \cdot Re^{-0.5223} \cdot \frac{h}{p}^{0.864} \quad (2)$$

$$Nu = 0.0479 \cdot Re^{0.7089} \cdot \frac{h}{p}^{0.30} \cdot Pr^{0.33} \quad (3)$$

Fig. 7 is a plot comparing correlations with CFD results, showing discrepancies within 15%. Additionally, to validate the reliability of the correlations, experimental results and interpretations from another group were compared, as illustrated in Fig. 8. The presented correlations exhibit discrepancies within 20% when compared to results from the other group's study [5,6].

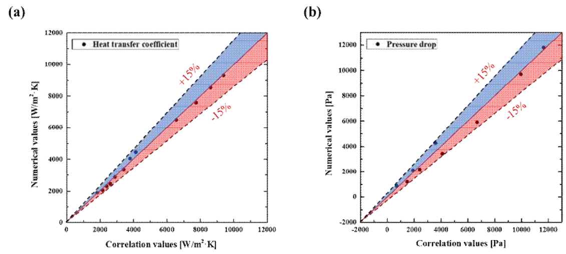

Fig. 7 Comparison of (a) HTC and (b) pressure drop (CFD vs. Correlation).

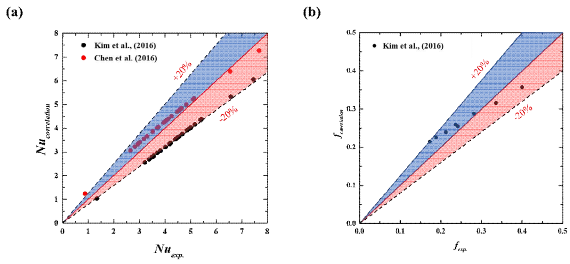

Fig. 8 Comparisons of (a) Nusselt number and (b) friction factor (Experimental data vs. correlations).

4. Conclusions

In this study, numerical analysis using ANSYS Fluent was conducted to evaluate the thermal-hydraulic performance of Printed Circuit Heat Exchangers (PCHEs) with zigzag channels at different bend angles. The bend angle of the zigzag channel ranged from 10 degrees to 40 degrees with a 10-degree interval, and the Reynolds number range was set from 300 to 2000.

We observed that at most Reynolds number ranges, a bend angle of 20-degree exhibited the highest comprehensive performance factor. This is because, for bend angles greater than 20-degree, strong vortices at the channel bend result in significant pressure drops.

Based on the CFD analysis results of this study, the new correlations for friction factor and Nusselt number are proposed, which are found to closely match the CFD analysis results of this study within ±15%. Furthermore, to validate the new correlation, comparisons were made with experimental and interpretational results from other studies, showing agreement within ±20%. This has provided a foundation for advantageous utilization of PCHE design in the design of small nuclear reactor systems, which have been receiving increasing attention recently.These research findings offer important guidelines for the design and optimization of PCHEs and are expected to be widely utilized in future related research and applications.

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