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Computational Study on Local Thermal-hydraulic Performance for Zigzag Printed Circuit Heat Exchanger with Various Pitches

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1. Introduction

A printed circuit heat exchanger (PCHE) is a promising heat exchanger due to its compact size and operability under high pressure and temperature. The PCHE is manufactured by using chemical etching and diffusion bonding. Since several millimeter sized flow channels are fabricated by chemical etching, the PCHE has large heat transfer area in small volume. The PCHE has been studied as the intermediate heat exchanger for the high temperature gas-cooled reactor and sodium-cooled fast reactor [1-4], and as the steam generator for the small modular reactor [5].

Various types of flow channel such as straight, zigzag, S-shape, and airfoil fin were considered as the flow channel of the PCHE [4]. The configuration of flow channel affects the thermal-hydraulic performance of the PCHE. For example, the PCHE with zigzag flow channel exhibits larger pressure loss and better heat transfer performance than the PCHE with straight flow channel. On the other hand, the PCHE with S-shape and airfoil fin flow channel shows smaller pressure loss than the PCHE with zigzag flow channel as well as better heat transfer performance than the PCHE with straight flow channel. The flow channel in the PCHE is selected according to its operation condition. The single or mixed type of the flow channel can be adopted in the PCHE [3].

The PCHE with zigzag flow channel is widely used due to simple geometry and good heat transfer performance. Its thermal-hydraulic performance is dependent on the shape factors such as the flow channel diameter, inclination angle, and pitch. Previous studies showed that both the heat transfer performance and pressure loss increase in the condition of large inclination angle and small pitch [2, 6]. They also presented the correlations of Fanning friction factor (*f*) and Nusselt number (Nu) to predict the local thermal-hydraulic performance required to determine the size of the PCHE, but those correlations were applicable to the small range of Reynolds number (Re).

In this paper, local thermal-hydraulic performance on PCHE with zigzag flow channel is numerically studied. The applicable range of Re is enlarged, and the effect of the pitch of the zigzag channel is investigated. The correlations of *f* and Nu as a function of Re, Prandtl number (Pr), and pitch are presented.

2. Methods and Results

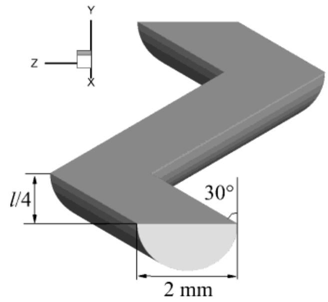

Fig. 1. Computational domain for the zigzag channel

2.1 Computational Method

Numerical simulations were performed by using commercial computational fluid dynamics (CFD) code, FLUENT 13.0. The steady-state, incompressible, and turbulence flow was simulated, where thermophysical properties was assumed to be constant. SIMPLE algorithm and SST *k-ω* method were used for the pressure-velocity coupling and turbulence modeling, respectively. The fluid flow analysis and heat transfer analysis were separately conducted because they were not coupled in this calculation. The fluid flow analysis was firstly conducted, and then the heat transfer analysis was followed on the calculated fluid flow field.

In this paper, the zigzag channel with semicircular cross-section was considered, and only the single pitch of the flow channel was included in the calculation domain to reduce the computational cost [3] as shown in Fig. 1. The periodic condition was employed at the inlet and outlet. The other walls were treated as a no-slip wall with a constant temperature. The channel diameter and inclination angle were set as 2 mm and 30°, respectively. The pitches of l = 8, 12, 16, 20 mm were considered.

2.2 Grid Sensitivity Test

The grid sensitivity test was conducted for the zigzag channel with the pitch of 12 mm at the Re of 170,000 and Pr of 1.25. Three cases with different number of cells were tested, and *f* and Nu were compared. *f* is calculated by

$$f = \left(\frac{dP}{dx}\right)\frac{D_h}{2\rho V_{avg}^2}\ , \qquad (1)$$

where D_h, ρ, and V_{avg} are the hydraulic diameter, fluid density, and average fluid velocity, respectively. The derivative dP/dx is the pressure gradient through the flow channel. Nu is calculated by

$$\mathrm{Nu} = \left(\frac{Q_{wall}}{A_{wall}}\right)\frac{D_h}{k\Delta T}, \quad (2)$$

where Q_{wall}, A_{wall}, k, and $\triangle T$ are the heat transfer rate through top and lower circumferential walls, area of top and lower circumferential walls, fluid thermal conductivity, and temperature difference between the bulk fluid and wall, respectively. The results are presented in Table I. Since discrepancies of f and Nu among the three cases were not large, the number of cells for Case 2 was selected for other computations.

2.3 Comparison with Previous Studies

For a comparison with previous studies of Kim and No [2] and Chen et al. [7], the calculations were conducted for the zigzag channel with the channel diameter of 2 mm, inclination angle of 15°, and pitch of 24.6 mm respectively. Pr was set as 0.66. The present results agree well with previous studies, as shown in Table II.

2.4 Results of Fluid Flow Analysis

The fluid flow analyses were conducted for selected Re and l/D_h. A correlation for f as a function of Re and l/D_h was derived based on the CFD results as follows:

$$f = \left[2.227\left(l/D_h\right)^{-1.344} + 0.0663\right]\mathrm{Re}^{-0.116} + \frac{24.556}{\mathrm{Re}}, \quad (3)$$

which is valid for $1{,}000 \le \mathrm{Re} \le 170{,}000$ and $6.55 \le l/D_h \le 16.37$. Fig. 2 shows f obtained from both the CFD results and Eq. (3). The discrepancy between them was not large and the maximum error was only 4.67 %. The results also show that f is decreased as Re or l/D_h is increased.

Table I: Results for grid sensitivity test

	Case 1	Case 2	Case 3
Number of cells	977,408	2,027,520	5,777,920
f	0.0402	0.0417	0.0422
Nu	697.63	733.28	748.19

Table II: Comparison of f and Nu

	Re	Present study	Kim and No [2]	Chen et al. [7]
f	2,000	0.0227	0.0240	0.0210
	2,500	0.0207	0.0217	0.0190
Nu	2,000	11.103	9.840	10.611
	2,500	12.900	11.058	12.267

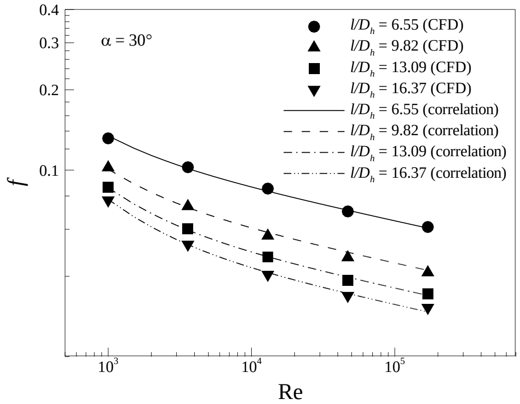

Fig. 2. Fanning friction factor obtained from the CFD analyses and Eq. (3).

2.5 Results for Heat Transfer Analysis

The heat transfer analyses were conducted for selected Re, Pr and l/D_h. A correlation for Nu as a function of Re, Pr, and l/D_h was derived based on the CFD results as follows:

$$\mathrm{Nu} = \mathrm{Re}^{\left[-0.000536\left(l/D_h\right)^2 + 0.0203\left(l/D_h\right) + 0.694\right]} \times \mathrm{Pr}^{0.593}\left[0.562\left(l/D_h\right)^{-1.338}\right] + 2.093, \quad (4)$$

which is valid for $1{,}000 \le \mathrm{Re} \le 170{,}000$, $0.8 \le \mathrm{Pr} \le 1.25$, and $6.55 \le l/D_h \le 16.37$. Figs. 3-5 show Nu obtained from both the CFD results and Eq. (4). The maximum discrepancy was only 8.33 %. The results also shows that Nu decreases as l/D_h increases, but Nu increases as Re or Pr increases.

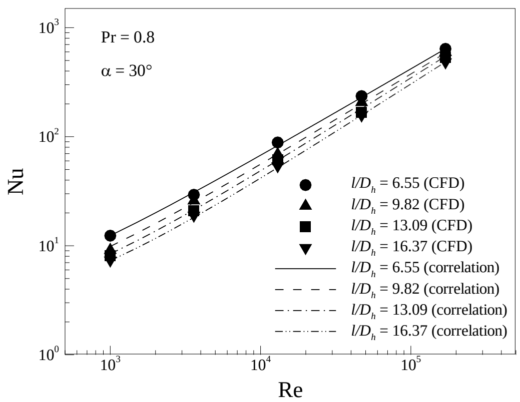

Fig. 3. Nusselt number obtained from the CFD analyses and Eq. (4) at Pr = 0.8.

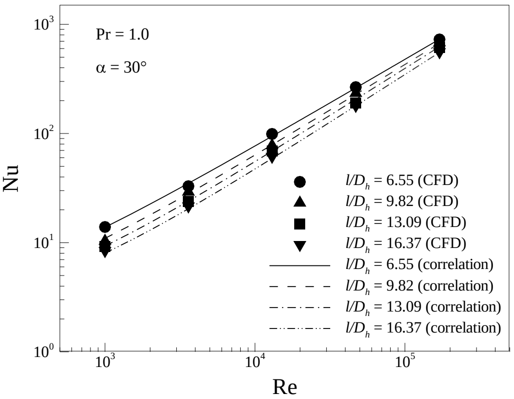

Fig. 4. Nusselt number obtained from the CFD analyses and Eq. (4) at Pr = 1.0.

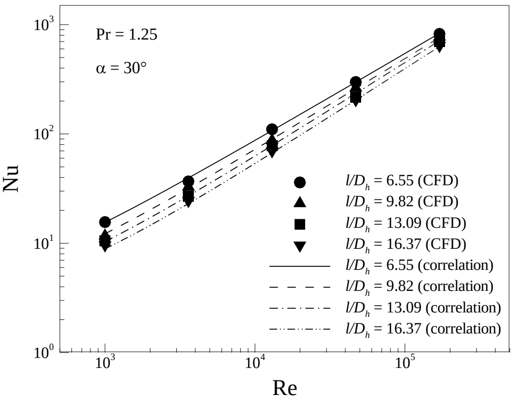

Fig. 5. Nusselt number obtained from the CFD analyses and Eq. (4) at Pr = 1.25.

3. Conclusions

The CFD analyses were conducted to obtain the local thermal-hydraulic performance on the zigzag PCHE with the semicircular cross-section and various pitches. As a result, the correlations for f and Nu expressed as a function of non-dimensional numbers were obtained in the range of Re from 1,000 to 170,000, Pr from 0.8 to 1.25, and l/D_h from 6.55 to 16.37. They showed good agreement with CFD result, and can be utilized for sizing of the PCHE using the system analysis code. The results also showed that f is small for the zigzag channel with large pitch at high Re condition, and Nu is large for the zigzag channel with small pitch at high Re and Pr conditions.

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