Preliminary Computational Study on Local Thermal-hydraulic Performance for Zigzag Flow Channel of Printed Circuit Heat Exchanger

C. B. Chang [*], Y. Bae, H. Cho, Y. I. Kim, S. J. Kim
Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
[*]*Corresponding author: cbchang@kaeri.re.kr*

1. Introduction

Among various types of the heat exchanger, a printed circuit heat exchanger (PCHE) is a compact heat exchanger with an excellent heat transfer performance. The flow paths of several millimeter size are fabricated on each sheet by chemical etching, and the sheets are bonded as one block by diffusion bonding. Hence, the PCHE has enormously large heat transfer area, and can be operated under high temperature and pressure conditions. The PCHE has been considered as an intermediate heat exchanger (IHX) for the high temperature gas-cooled reactor and sodium-cooled fast reactor [1-4]. Recently, the PCHE has been proposed as a steam generator (SG) for the small modular reactor (SMR) [5].

Various types of the flow channel, such as straight, zigzag, and airfoil fin types, can be adopted in the PCHE [4]. The thermal-hydraulic performance of the PCHE has been studied by both the experiment and computation. The computational approach is useful to provide the local thermal-hydraulic performance of the PCHE, which is required to determine the size of the PCHE using the system analysis code [1]. Since most of previous studies consider the PCHE as the IHX, the local thermal-hydraulic performance of the PCHE with semicircular zigzag flow channel is mainly studied at the operating condition of the IHX.

In this paper, the PCHE with circular zigzag flow channel is considered as the SG, and the local thermal-hydraulic performance of the PCHE is numerically studied. The correlations for the Fanning friction factor (f) and Nusselt number (Nu) at the operating condition of the SG for the SMR are presented.

2. Methods and Results

2.1 Computational Setup

Computational fluid dynamics (CFD) analyses were conducted using FLUENT 13.0 code. In the simulations, steady-state, incompressible, and turbulent flow with constant thermophysical properties was assumed. SIMPLE algorithm was used for the pressure-velocity coupling, and the SST k-ω method was adopted for the turbulence modeling. In this paper, the circular flow channel was considered to reduce the flow resistance [5], but only the single pitch of the semicircular flow channel was included in the calculation domain to

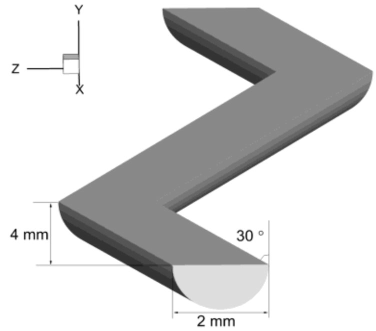

Fig. 1. Computational domain for the zigzag channel

reduce the computational cost [3] as shown in Fig. 1. Hence, the symmetric condition was adopted on the top surface, and the periodic condition was employed at the inlet and outlet. The lower circumferential wall was treated as a no-slip wall with a constant temperature. The flow channel diameter, pitch, and inclined angle were set as 2 mm, 16 mm, and 30°, respectively.

2.2 Grid Sensitivity Test

The grid sensitivity test was conducted with the Reynolds number (Re) of 99,884 and Prandtl number (Pr) of 0.96. Three cases were tested, and f and Nu were compared. f is calculated by

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

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 path. Nu is calculated by

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

where Q_{wall}, A_{wall}, k, and ΔT are the heat transferred from lower circumferential wall, lower circumferential wall area, fluid thermal conductivity, and temperature difference between the bulk fluid and lower circumferential 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 1 was used for other computations.

Table I: Results for grid sensitivity test

	Case 1	Case 2	Case 3
Number of cells	1,477,200	4,651,800	10,878,400
f	0.0486	0.0480	0.0463
Nu	406.84	410.43	414.79

2.3 Results for fluid flow

Since an incompressible flow without gravity effect was considered, the fluid flow and heat transfer were not coupled. For efficient calculation, the fluid flow was calculated without heat transfer analysis. Since the operating condition of the SG is included in the range of Re from 2,000 to 100,000, the computation was conducted for selected Re within the range. A correlation for f as a function of Re was derived based on the CFD results as follows:

$$f = 0.0469 + 14.061\mathrm{Re}^{-0.784}, \tag{3}$$

which is valid for $2{,}000 \le \mathrm{Re} \le 100{,}000$. Fig. 2 shows f obtained from both the CFD results and Eq. (3). The discrepancy between them was not large and the maximum was only 5.5 %. Therefore, they exhibited good agreement.

2.4 Results for heat transfer

The operating condition of the SG is included in the range of Pr from 0.8 to 1.25 as well as Re from 2,000 to 100,000. Only the heat transfer was calculated for selected Pr on the flow field calculated in Section 2.3. A correlation for Nu as a function of Re and Pr was derived based on the CFD results as follows:

$$\mathrm{Nu} = 5.938 + 0.0214\mathrm{Re}^{0.86}\mathrm{Pr}^{0.555}, \tag{4}$$

which is valid for $2{,}000 \le \mathrm{Re} \le 100{,}000$ and $0.8 \le \mathrm{Pr} \le 1.25$. Fig. 3 shows Nu obtained from both the CFD results and Eq. (4). The maximum discrepancy was merely 2.29 %, which shows that Eq. (4) predicts Nu well under the conditions considered in this paper.

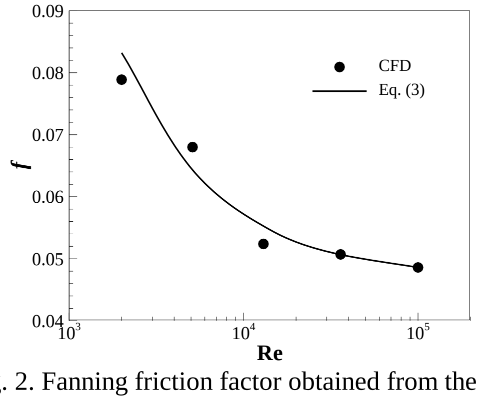

Fig. 2. Fanning friction factor obtained from the CFD analyses and Eq. (3).

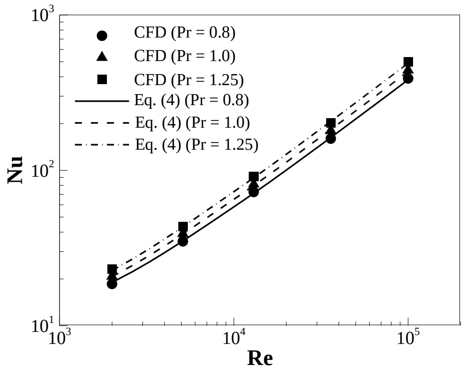

Fig. 3. Nusselt number obtained from the CFD analyses and Eq. (4).

2.5 Comparison with correlations for straight flow channel

The correlations for f and Nu of zigzag flow channel were compared with those of straight flow channel, showing the effect of the geometry for the pressure drop and heat transfer. The correlations for f and Nu of straight flow channel are as follows [6]:

$$f = \left(0.790\ln\mathrm{Re} - 1.64\right)^{-2} / 4, \tag{5}$$

$$\mathrm{Nu} = \frac{(f/2)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/2)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}. \tag{6}$$

Eq. (5) is valid for $3{,}000 \le \mathrm{Re} \le 5{,}000{,}000$, and Eq. (6) is valid for $3{,}000 \le \mathrm{Re} \le 5{,}000{,}000$ and $0.5 \le \mathrm{Pr} \le 2{,}000$. Hence, f and Nu for selected Re and Pr were calculated by Eqs. (3) and (4) for the zigzag flow channel and by Eqs. (5) and (6) for straight flow channel, respectively.

The results are summarized in Table II, which shows that both the pressure drop and heat transfer for zigzag flow channel are large compared to the straight channel. The ratios of f between zigzag and straight flow channels are increased with the increase of Re, but Nu ratios are similar regardless of Re and Pr.

Table II: Fanning friction factor and Nusselt number for straight and zigzag flow channels

		Straight pipe		Zigzag pipe	
Re	Pr	f	Nu	f	Nu
5,100	0.8	0.00960	17.916	0.0643	35.122
	1.25		21.549		43.324
13,000	0.8	0.00732	39.320	0.0553	71.194
	1.25		48.886		89.535
36,000	0.8	0.00566	87.345	0.0507	162.631
	1.25		111.641		206.671
100,000	0.8	0.00450	194.300	0.0486	383.188
	1.25		253.796		489.218

3. Conclusions

The CFD analyses are conducted to obtain the local thermal-hydraulic performance on the PCHE with the circular zigzag channel. The PCHE is considered as the SG for the SMR, and its operating condition is considered. As a result, the correlations for f and Nu expressed as a function of non-dimensional numbers are obtained in the range of Re from 2,000 to 100,000 and Pr from 0.8 to 1.25. They showed good agreement with CFD result, and can be utilized for sizing of the PCHE using the system analysis code. The correlations were also compared with those for circular straight channel, which shows that the pressure drop and heat transfer for zigzag channel is larger than those for straight channel. The rate of increase in f between the straight and zigzag flow channels is increased at high Re, but Nu ratios between the straight and zigzag flow channels remains similar even at the high Re and Pr.

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