Preliminary Estimation of Channel Deformation and Heat Transfer Performance in a Printed Circuit Heat Exchanger

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1. Introduction

Printed Circuit Heat Exchangers (PCHEs) are widely used for industry application, such as cryogenic storages, evaporators and reactors. A PCHE has strength in high temperature and high pressure operating conditions. Therefore, A PCHE is considered as a candidate intermediate heat exchanger type for a high temperature gas cooled reactor (HTGR).

PCHE design and manufacturing processes are well established for using stainless steel materials. The uncertainties from design and manufacturing processes are allowable for normal industrial applications using stainless steel because design margin is mostly enough. However, there is a lack of knowledge about the uncertainties for some extreme applications, which are HTGR application and hydrogen station, for example.

A channel is usually assumed as semicircle in the design stage but the product is not perfect semicircle after chemical etching and diffusion bonding. The deformed channels may increase the pressure difference and decrease the heat transfer performance. These uncertainties may reduce the design margin and the life time of the PCHE.

The effect of longitudinal heat conduction is one of the design uncertainties when a simple LMTD method is used [1]. The estimation of channel deformation during manufacturing process is required in terms of engineering. Ni-based alloy is used for the extreme applications. Channel deformation and heat transfer performance are preliminarily estimated in the present study.

2. Methods and Results

In this section some of the techniques used to measure dimension of a PCHE channel are described. The material of the PCHE was SS316L. More than two hundred plates are diffusion bonded after etching process.

2.1 Computer Image Processing

The cross-sectional images of the channels were obtained with SEM. The obtained images were processed to measured dimensional parameters. SciPy, NumPy and OpenCV, open source libraries, were used based on Python language [2]. SciPy was used for the filtering process. OpenCV was utilized for measuring area and perimeter. Fig. 1 shows a raw image and a processed image. OpenCV library detects contours with red lines.

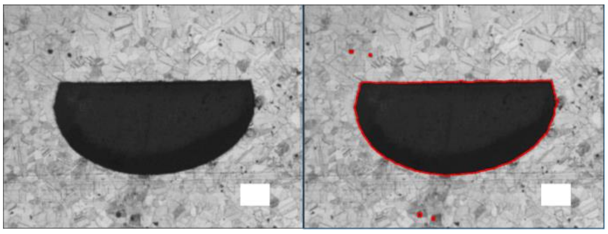

Fig. 1 raw Image and computer processed image

2.2 Estimation of Channel Deformation

The measured dimensional parameters are summarized in Table I. Fifteen cases with different locations are listed in the table.

Table I Summary of dimensional parameters of PCHE channel

Case	Area (mm^2)	Perimeter (mm)	Hydraulic Diameter (mm)	Diameter (mm)	Depth (mm)
1	1.22	4.94	0.99	1.69	0.83
2	1.23	4.85	1.02	1.70	0.82
3	1.34	6.26	0.85	1.74	0.84
4	1.30	4.87	1.07	1.72	0.86
5	1.25	5.05	0.99	1.71	0.82
6	1.33	4.92	1.09	1.72	0.89
7	1.33	5.10	1.05	1.74	0.85
8	1.12	4.64	0.97	1.64	0.79
9	1.33	4.95	1.07	1.77	0.86
10	1.37	5.07	1.08	1.75	0.88
11	1.25	4.86	1.03	1.69	0.82
12	1.26	4.87	1.04	1.72	0.84
13	1.36	5.34	1.02	1.73	0.87
14	1.33	5.29	1.00	1.73	0.87
15	1.25	4.84	1.03	1.70	0.82
Average	1.29	5.06	1.02	1.72	0.85
σ	0.07	0.38	0.06	0.03	0.03

The shape of channels was not perfect semicircle.

Therefore, channel diameter and channel depth were defined as Fig. 2.

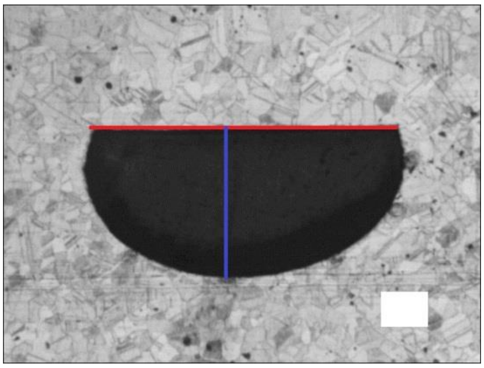

Fig. 2 Red line shows the diameter and blue line shows the depth.

The designed value of the diameter was 1.5 ㎜ but the output value was about 1.72 ㎜ after etching and diffusion bonding processes. It is considered that conventional etching and diffusion bonding process has a tolerance in order of 0.1 ㎜.

The dimensional parameters of the product channel are compared with that of ideal semicircle in Table II.

Table II Comparison of dimensional parameter between semicircle and real channel

	Ideal semicircle	Real channel
Diameter (㎜)	1.5	1.72
Cross-sectional Area ($㎜^2$)	0.88	1.29
Perimeter (㎜)	3.86	5.04
Hydraulic Diameter (㎜)	0.92	1.03
P/D_h	4.21	4.91
P/A	4.36	3.91
D_h/A	1.04	0.80

2.3 Estimation of Heat Transfer Performance

Heat transfer was considered in terms of a conductance, which is product of a heat transfer coefficient and total heat transfer area. First, the Nusselt number is a constant for straight PCHE channel in laminar flow [3]. The heat transfer coefficient is inversely proportional to the hydraulic diameter when the Nusselt number is the same.

$$\mathrm{Nu} = \frac{h \cdot D_h}{k} \tag{1}$$

$$h \sim \frac{1}{D_h} \tag{2}$$

The total heat transfer area is proportional to perimeter when the length is the same.

$$A_{tot} \sim P \tag{3}$$

The conductance is as follows:

$$hA_{tot} \sim \frac{P}{D_h} \tag{4}$$

The real channel has better heat transfer performance than the ideal semicircle based on the value of the perimeter over hydraulic diameter in Table II. However, the margin in the structural design is reduced with increase in the diameter.

Second, the Nusselt number is proportional to Reynolds number for the zig-zag channel [4].

$$\mathrm{Nu} = 4.089 + 0.00365 \cdot \mathrm{Re}^{1.0} \cdot \mathrm{Pr}^{0.58} \tag{5}$$
$$0 < \mathrm{Re} < 2500, 0.66 < \mathrm{Pr} < 13.41$$

$$\mathrm{Nu} \sim \mathrm{Re} \tag{6}$$

By combining equation (1) and (6) we obtain:

$$h \sim \frac{\mathrm{Nu}}{D_h} \sim \frac{\mathrm{Re}}{D_h} \tag{7}$$

$$\mathrm{Re} = \frac{\rho v D_h}{\mu} = \frac{\dot{m} \cdot D_h}{A \cdot \mu} \tag{8}$$

We assumed that the mass flow rate in each channel is the same.

$$\mathrm{Re} \sim \frac{D_h}{A} \tag{9}$$

By combining equation (3) and (5), we obtained:

$$h \sim \frac{1}{A} \tag{10}$$

We obtained the conductance as follows:

$$hA_{tot} \sim \frac{P}{A} \tag{11}$$

The parameter *P/A* of the ideal semicircle with 1.5 ㎜ in diameter is about 10.5 percent higher than that of the real channel. Therefore, the heat transfer performance of the product is lower than that of the design.

Third, in turbulent flow regime, Dittus-Boelter equation is applicable to a PCHE.

$$\mathrm{Nu} = 0.023\mathrm{Re}^{0.8} Pr^n \tag{12}$$

$$hA_{tot} \sim \left(\frac{D_h}{A}\right)^{0.8} \left(\frac{P}{D_h}\right) \tag{13}$$

The heat transfer performance of the product is also lower than that of the design.

3. Conclusions

A PCHE channel usually is design to semicircle shape. We ordered PCHE with 1.5 mm in diameter but the product was 1.72 mm in diameter. A careful quality assurance is required for high temperature and high pressure application.

It is deformed during etching and diffusion bonding process although the processes are well proven. It has a negative effect in terms of the heat transfer and the structural integrity. On the other hand, a positive effect was obtained in terms of the heat transfer for a straight channel.

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