Preliminary Computational Study on Conduction Thermal Resistance for a Printed Circuit Heat Exchanger with Monitoring Channels

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1. Introduction

Printed circuit heat exchanger (PCHE) is a promising heat exchanger due to its advantage of in compactness and excellent heat transfer performance. The PCHE is widely used for industrial applications such as off shore oil and gas processing, and floating LNG devices [1]. The PCHE is also applied to nuclear industry. The PCHE has been proposed as an intermediate heat exchanger for high temperature gas-cooled reactors and sodium-cooled fast reactors [2-4]. The PCHE has been studied as a steam generator (SG) for pressurized water reactors (PWRs) [5].

The U-tube and helical-tube SGs have been widely used for the PWRs. Since in-service inspection is required for maintenance of the SG, the integrity of the SG tube is regularly inspected. However, the cross-sectional area of flow channels for the PCHE is too smaller than that for the other types of SG, so that direct inspection of the flow channels for the PCHE is considered to be impossible. To tackle such problem of the PCHE, concept of a monitoring channel was introduced [6]. The monitoring channel is much smaller than main flow channel, and is added between the main flow channels in a sandwich structure. If a crack occurs in the PCHE from the primary or secondary side channels, the fluid inside the primary or secondary side channels will leak to the monitoring channels. Since the conditions of the monitoring channel are continuously monitored, on-line monitoring of the integrity for the PCHE is enabled during a normal operation.

The addition of the monitoring channel in the PCHE disturbs heat transfer from the primary side to the secondary side. Since the monitoring channel may degrade the thermal performance of the PCHE, optimization of the monitoring channel is required. In this study, the conduction thermal resistance of the PCHE with monitoring channel was calculated to examine the effect of the monitoring channel on the performance of the PCHE. In the simulation, the various sizes and arrangements of the monitoring channel were considered.

2. Methods and Results

2.1 Computational Setup

Three-dimensional thermal conduction analyses were performed using FLUENT code. The steady-state and constant properties were assumed in the simulations. As shown in Fig. 1, the cross section of all the channels are semi-circle. The red, blue, green, and gray regions indicate the primary side channel, secondary side channel, monitoring channel, and solid region, respectively. The depth of the primary and secondary side channels is 1 mm. The horizontal distance between neighboring flow channels in the same side is 2 mm, while the vertical distance between the primary and secondary side channels is 1 mm. Three types of monitoring channel depths are assumed: 0.2, 0.25, and 0.35 mm. The arrangement of each monitoring channel was set considering the ratio of total bonding area and stack area for the monitoring channels, which were 0.42, 0.43, and 0.42 for the depth of 0.2, 0.25, and 0.35 mm, respectively. The convective boundary condition was adopted on the walls for primary and secondary side channels. Hence, the heat transfer coefficients of 50,000 and 25,000 $W/m^2 \cdot K$ and the temperature of 400 and 300 K were imposed on the primary and secondary side channels, respectively. The heat flux on the monitoring channel was assumed as zero. The periodic boundary conditions were employed at the other walls.

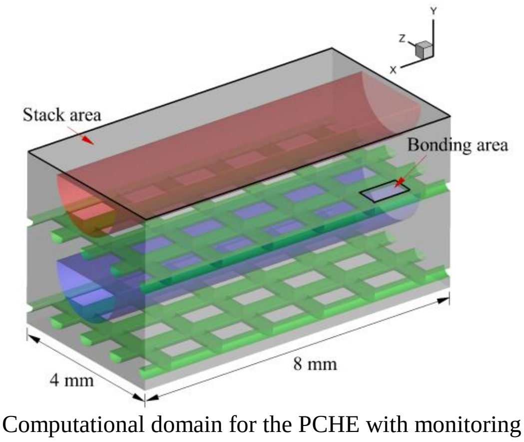

Fig. 1. Computational domain for the PCHE with monitoring channels.

2.2 Effects of the size of the monitoring channels

The conduction analyses for the PCHE with the monitoring channels were performed, where the depth of 0.2, 0.25, and 0.35 mm were used for the monitoring channels. For comparison of the results, a conduction analysis for the PCHE without the monitoring channel was also performed. The conduction thermal resistance was calculated to compare the effective conductivity of the PCHE with the monitoring channels of different sizes, which was defined by

$$R_c = \frac{\Delta T}{Q}, \quad (1)$$

where R_c, $\triangle T$, and Q are the conduction thermal resistance, temperature difference between the primary and secondary side channel walls, and heat transfer rate between the primary and secondary side channel walls, respectively.

The conduction thermal resistances obtained from the conduction analyses were summarized in Table I. The conduction thermal resistance increased with the increase of the depth of the monitoring channels, and the PCHE without the monitoring channels had the smallest conduction thermal resistance.

Figures 2-4 show the temperature distribution of the PCHE on the *y-z* plane. The temperature gradient for the PCHE without the monitoring channel was the steepest on the vertical centerline, which is the shortest path for the conduction heat transfer. The temperature gradient near the flow channels for the PCHE with the monitoring channels generally decreased as the size of the monitoring channel increased. Since one of the monitoring channel is aligned with the flow channels along the *y*-direction, the location of the shortest path for the conduction heat transfer is changed for the PCHE with the monitoring channel. Furthermore, the length of the shortest path for the conduction heat transfer was increased. Therefore, the conduction thermal resistance for the PCHE with the monitoring channel was increased as the size of the monitoring channel increased.

As the size of the monitoring channel increased, the distances among the monitoring channels along the *z*- and *x*-directions were also increased. Therefore, the bonding area for the monitoring channels increased with the increase of the size of the monitoring channel although the total bonding area was almost same in all the simulations. Since the bonding area became the minimum area for the detection of the crack, the monitoring channel of small size with small conduction thermal resistance is more suitable for the design of the monitoring channels.

Table I: Conduction thermal resistances for the PCHE with and without the monitoring channels

Depth of monitoring channels (mm)	No monitoring channel	0.2	0.25	0.35
Conduction thermal resistance (K/W)	2.94	3.86	4.04	4.59

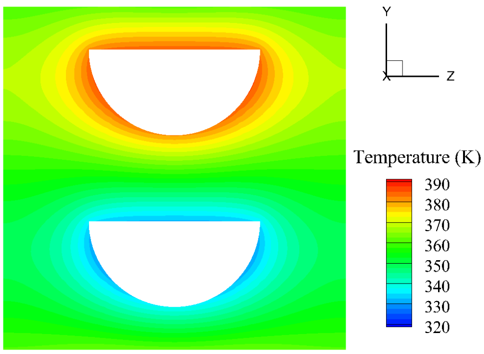

Fig. 2. Temperature distribution of the PCHE without the monitoring channels.

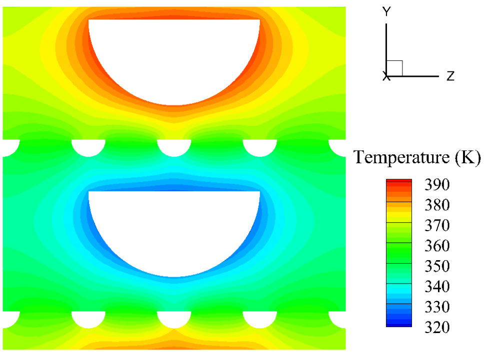

Fig. 3. Temperature distribution of the PCHE with the monitoring channels of depth 0.2 mm.

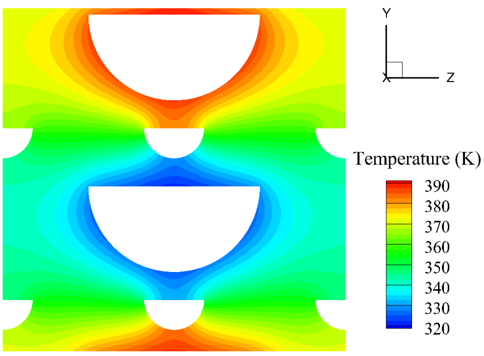

Fig. 4. Temperature distribution of the PCHE with the monitoring channels of depth 0.35 mm.

2.3 Effects of the arrangement of the monitoring channels

The conduction analyses for the PCHE with the monitoring channels were performed when the monitoring channel was not aligned with the flow channels along the *y*-direction. The conduction thermal resistance was calculated for the PCHEs with the monitoring channels of different sizes, which were summarized in Table II. As shown in Tables I and II, the conduction thermal resistances were not much different regardless of the alignment of the monitoring and flow channels.

Table II: Conduction thermal resistances for the PCHE with and without the staggered monitoring channels

Depth of monitoring channels (mm)	No monitoring channel	0.2	0.25	0.35
Conduction thermal resistance (K/W)	2.94	3.86	4.07	4.48

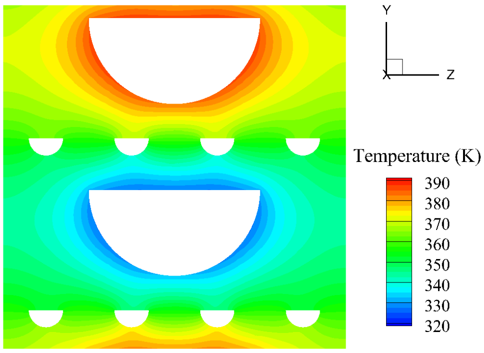

Fig. 5. Temperature distribution of the PCHE with the staggered monitoring channels of depth 0.2 mm.

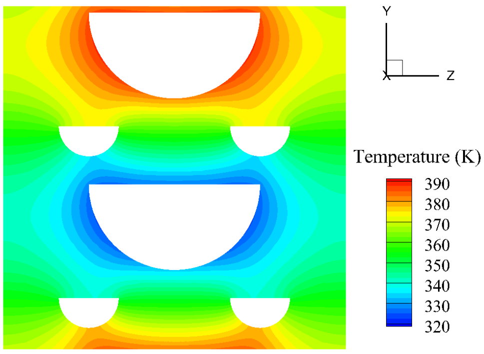

Fig. 6. Temperature distribution of the PCHE with the staggered monitoring channels of depth 0.35 mm.

Figures 5 and 6 show the temperature distribution of the PCHE with staggered monitoring channels on the *y-z* plane. As the monitoring channels shifted, the shortest path of the conduction heat transfer was maintained along the vertical centerline, like the PCHE without the monitoring channel. However, the temperature gradient along the vertical centerline decreased due to the effect of the monitoring channels.

The arrangement of the monitoring channels was not important for the aspect of the performance of the PCHE. However, as the function of the monitoring channel is considered, the monitoring channel aligned with the flow channels is more appropriate. In this arrangement, the monitoring channel is located on the region with the smallest thickness between the flow channels.

3. Conclusions

The thermal conduction analyses were performed to examine the effects of the monitoring channels on the performance of the PCHE. Three types of monitoring channel depths and two types of arrangements of the monitoring channels were considered. The conduction thermal resistance was calculated for each case, and was compared with that of the PCHE without the monitoring channels. The results show that the conduction thermal resistance increased with the increase of the size of the monitoring channels. The effects of the alignment of the monitoring and flow channels on the conduction thermal resistance were small. As a result, the small sized monitoring channels aligned with the flow channels are more suitable for design of the PCHE with the monitoring channels when considering the monitoring function and thermal performance.

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