Development of Conduction Thermal Resistance Correlation for Solid Region of Printed Circuit Steam Generator Including Monitoring Channels

C. B. Chang [*], J. H. Moon, H. Cho, H. S. Han, S. Ryu
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

A printed circuit steam generator (PCSG) is a diversion of a printed circuit heat exchanger (PCHE) designed as a steam generator (SG). The PCSG is recently studied to replace the U-tube and helical-type SGs in the nuclear industry [1-3]. The PCSG is fabricated in a same manner with the PCHE, and mini-channels of the PCSG provide a large heat transfer area with higher heat transfer performance. When the PCSG is adopted in the reactor, the size of the reactor can be reduced without decrease of the thermal power.

Direct inspection of the SG tube is required for the regular inspection of SG integrity. However, the direct inspection for the mini-channels of the PCSG may be hard due to their tiny size, huge number, and complex geometries. As an alternative method for the inspection of the PCSG, the monitoring channels were proposed [4], which were located between the primary and secondary side flow channels of the PCSG. The integrity of the PCSG can be continuously monitored through real-time detection of the leakage from the main flow channels to the monitoring channels.

The effect of the monitoring channels on the thermal performance of the PCHE was investigated in the previous studies [5, 6]. The thermal conduction analyses were performed for solid region including all the flow channels as well as the monitoring channels. The results showed that the monitoring channels degraded the thermal performance of the PCHE. The conduction thermal resistance increased as size of the monitoring channel increased. The effect of the vertical alignment between the main flow channels and monitoring channels decreased as the size of the monitoring channels decreased.

In this study, the conduction analyses were performed for the solid region including the unit monitoring channel. Various horizontal distances between neighboring monitoring channels were examined, and the correlation was developed to predict the conduction thermal resistance. The conduction thermal resistance for the solid region including straight main flow channels and monitoring channels was estimated using the correlation in the present study and the results of the previous study [5].

2. Methods and Results

2.1 Computational Setup

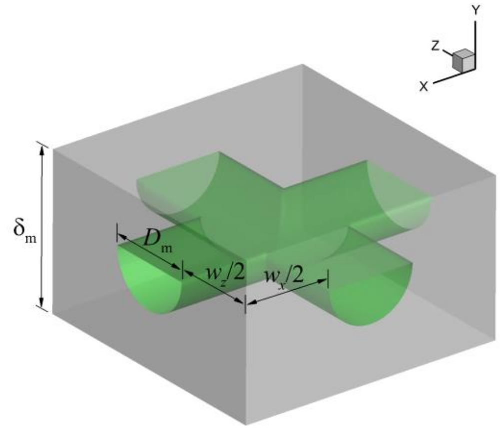

Fig. 1. Computational domains for the solid region including unit monitoring channel.

Three-dimensional conduction heat transfer analyses for solid region were performed by using ANSYS, where the steady-state and constant properties were assumed. Computational domain is shown in Fig. 1, which shows the solid region including the unit monitoring channel indicated as green wall. The monitoring channel is a straight flow channel with the cross section of semi-circular shape, and is connected like a net. In this figure, δ_m, D_m, w_x, and w_z indicate thickness of the solid region, diameter of the monitoring channel, and horizontal distance between neighboring monitoring channels in *x*- and *z*-direction, respectively.

In the computation, D_m was fixed as 0.4 mm. On the other hand, δ_m varied from 0.5 to 0.9 mm and w_x & w_z varied from 0.6 to 1.2 mm, respectively. Adiabatic boundary condition was imposed on the monitoring channel walls, and constant temperature condition was imposed on the top and bottom walls. Periodic boundary condition was adopted on the other walls.

2.2 Conduction Thermal Resistance for Solid Region Including the Monitoring Channels

The conduction analyses were carried out for the solid region including the unit monitoring channel of the various arrangements. The area normalized conduction thermal resistance was calculated as follows:

$$\langle RA \rangle_m = \frac{\Delta T}{Q} A_s, \tag{1}$$

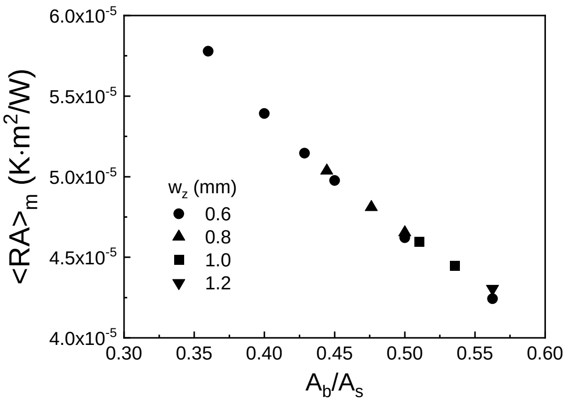

Fig. 2. Conduction thermal resistance obtained from the CFD analyses for δ_m = 0.5 mm.

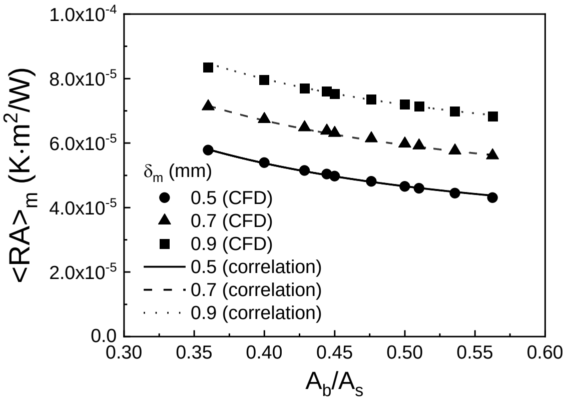

Fig. 3. Conduction thermal resistance obtained from the CFD analyses and correlation for δ_m = 0.5, 0.7, and 0.9 mm.

where R, A_s, $\triangle T$, and Q are the conduction thermal resistance, stack area, temperature difference between the top and bottom walls, and heat transfer rate between the top and bottom walls, respectively. Here, the stack area A_s indicates the cross-sectional area of the whole computational domain in *zx*-plane.

The calculation was conducted for δ_m = 0.5, 0.7, and 0.9 mm. Combinations of w_x and w_z were variously considered because they were related to the arrangement of the monitoring channels. The bonding area ratio was defined as the ratio of the total bonding area and stack area to represent the arrangement of the monitoring channels, which was calculated by

$$\frac{A_b}{A_s} = 1 - \frac{D_m\left(D_m + w_z + w_x\right)}{\left(D_m + w_z\right)\left(D_m + w_x\right)}\,. \tag{2}$$

Figure 2 shows the variation of the conduction thermal resistance according to the bonding area ratio for δ_m = 0.5 mm. The conduction thermal resistance decreased as the bonding area ratio increased, which indicated that the small number of the monitoring channel was preferred for high heat transfer performance of the PCSG. The difference in the conduction thermal resistance was negligible if the bonding area ratio was the same, although w_x and w_z were different. Therefore, the effect of the monitoring channel arrangement on the conduction thermal resistance can be simply expressed using the bonding area ratio without details of the arrangement.

The calculations were also conducted for δ_m = 0.7 and 0.9 mm. The correlation for the conduction thermal resistance was developed using the CFD results as follows:

$$\langle RA\rangle_m = 0.381\left(\frac{\delta_m}{D_{h,m}}\right)^{0.196}\left(\frac{D_{h,m}}{k}\right)\left(\frac{A_b}{A_s}\right)^{-1.516} + \frac{\delta_m}{k}, \tag{3}$$

where $D_{h,m}$ and k indicate the hydraulic diameter of the monitoring channel and thermal conductivity of the solid, respectively. The conduction thermal resistance for solid region including the monitoring channel can be predicted using Eq. (3) in the range of $2.05 \le \delta_m/D_{h,m} \le 3.68$, and $0.36 \le A_b/A_s \le 0.56$. The maximum error between the CFD result and correlation was 1.54 %. The results are shown in Fig. 3. The conduction thermal resistance decreased as δ_m decreased.

2.3 Estimation of the Conduction Thermal Resistance for PCSG Solid Region

The conduction thermal resistance of the PCHE with straight main flow channels and monitoring channels was estimated using Eq. (3) and the results of the previous study [5]. The conduction thermal resistance of the simple solid region of δ_m was subtracted from the conduction thermal resistance of the PCHE without monitoring channels, and the conduction thermal resistance obtained from Eq. (3) was added. The correction factor of 1.13 was used for Eq. (3) because the temperature near the monitoring channels was not constant unlike the boundary condition in the simulations. The different correction factor may be used for the other main flow channels. Such process can be expressed as follows:

$$\langle RA\rangle_{t,m} = \langle RA\rangle_t - \frac{\delta_m}{k} + 1.13\langle RA\rangle_m\,, \tag{4}$$

where $\langle RA\rangle_{t,m}$ and $\langle RA\rangle_t$ indicate the conduction thermal resistance for the PCHE with the monitoring channels and without the monitoring channels, respectively. Figure 4 shows the comparison of the estimated conduction thermal resistance and CFD result in the previous study [5]. They were much similar and the maximum error was 0.68 %, where $\delta_m/D_{h,m}$ of 2.05 was used for all the cases. The result shows that the whole conduction thermal resistance for the PCSG with the monitoring channel can be estimated if the conduction thermal resistance for the PCSG without the monitoring channel is prepared.

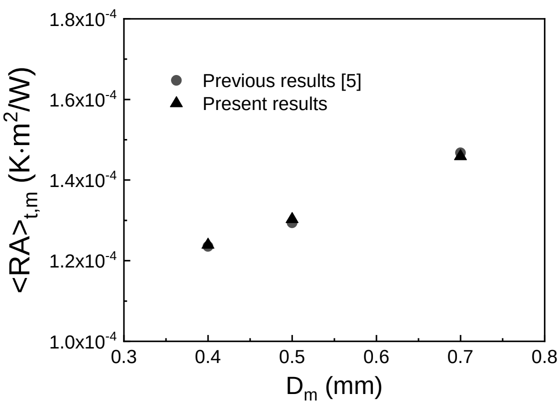

Fig. 4. Comparison of the conduction thermal resistance of the PCHE with monitoring channels.

3. Conclusions

The thermal conduction analyses were performed to develop the correlation for the conduction thermal resistance of the solid region including the monitoring channels. The various arrangements of the monitoring channel were considered. The effect of the monitoring channel arrangements on the conduction thermal resistance was represented using the bonding area ratio. The results showed that the conduction thermal resistance decreased as the bonding area ratio increased. The conduction thermal resistance of the PCHE with the monitoring channel was estimated using the correlation for the conduction thermal resistance developed in the present study and the conduction thermal resistance for the PCHE without the monitoring channel. The estimated conduction thermal resistance was similar to the CFD result for the PCHE with the monitoring channels.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (Ministry of Science and ICT) (No. NRF-2020M2D7A1079178).

REFERENCES

[1] C. W. Shin and H. C. No, Experimental Study for Pressure Drop and Flow Instability of Two-phase Flow in the PCHE-type Steam Generator for SMRs, Nuclear Engineering and Design, Vol.318, pp.109-118, 2017.
[2] H. S. Han, H.-O. Kang, J. Yoon, Y. I. Kim, K. K. Kim, and B. Choi, Experimental Investigation on Performance of a Printed Circuit Steam Generator for Integral Reactors, Proceedings of 9th Korea-Japan Symposium Nuclear Thermal Hydraulics and Safety, Nov.16–19, 2014, Buyeo, Korea.
[3] S. Kim, Y. I. Kim and S. J. Kim, Methodology of Unit Channel Thermal-Hydraulic Analysis for Performance Evaluation of Printed Circuit Steam Generators, Proceedings of KSME Fluid Engineering Division Conference, Apr.18–19, 2019, Gangneung, Korea.
[4] Y. I. Kim, Y. Bae, H. S. Han, and S. Kim, Heat Exchanger and Nuclear Power Plant Having the Same, Korean Patent, KR20170119246A, 2017.
[5] C. B. Chang, H. Cho, H. S. Han, and S. J. Kim, Preliminary Computational Study on Conduction Thermal Resistance for a Printed Circuit Heat Exchanger with Monitoring Channels, Transactions of the Korea Nuclear Society Virtual Autumn Meeting, Dec.17-18, 2020, Korea.
[6] C. B. Chang, J. H. Moon, H. Cho, H. S. Han, and S. J. Kim, Preliminary Computational Study on Conduction Thermal Resistance for a Zigzag Printed Circuit Heat Exchanger with Monitoring Channels, Transactions of the Korea Nuclear Society Virtual Spring Meeting, May.13-14, 2021, Korea.