Evaluation of Effective Thermal Conductivity Models for the VHTR fuel block

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1. Introduction

The Very High Temperature Reactor (VHTR) is one of the promising GEN-IV reactors due to its inherent safety features and its applications for hydrogen production. As a candidate for the VHTR design, the prismatic gas-cooled reactor, PMR200 [1], of which the core consists of hexagonal graphite block has been developed in Nuclear Hydrogen Development and Demonstration (NHDD) project of Korea. During the High Pressure Conduction Cooling (HPCC) or Low Pressure Conduction Cooling (LPCC) accidents where the coolant in the reactor is stagnant, the core is heated by the decay heated and then cooled down by conduction and radiation to the Reactor Cavity Cooling System across the prismatic core [2]. The fuel block which is hexagonal prism shape and included in the core contains 108 cylindrical coolant holes and 210 cylindrical fuel compacts. The heat transfer across the fuel block contains complex phenomena such as the solid conduction in the graphite and fuel compacts and the gas conduction and radiation heat transfer in coolant holes and bypass gaps.

For the verification of its inherent safety, it is of great importance to analyze the thermal distribution of the core. However, the detail calculation for the entire core demands excessive computation resources. Therefore GAMMA+ code [3] developed for an analysis of thermal-hydraulics and the safety of VHTR by KAERI regards a fuel block as a single homogenized medium. And the effective thermal conductivity model for the VHTR fuel block is necessary for the code.

In this study, several effective thermal conductivity models were introduced and validated by experiment and Computational Fluid Dynamics (CFD) analysis. For the experiment, the test blocks were composed of IG-11 graphite that is a material of VHTR fuel block and had same geometry with its fuel block. The experimental data were compared to the results of the models and CFD calculations.

2. Effective Thermal Conductivity Models

In the previous study [4], several Effective Thermal Conductivity (ETC) models were introduced and reviewed. The form of each model is as shown in Table I. Maxwell-based model is adopted as an ETC model for the fuel block in the GAMMA+ code. Radiation heat transfer is reflected in the form of an equivalent radiation heat transfer conductivity that is obtained as follows:

$$k_r = 4F\sigma\delta\overline{T}^3$$

where $F = \dfrac{1}{2[(1/\varepsilon)-1]+1/F_{12}}$.

The equivalent radiation heat transfer conductivity is added to gas conductivity. And the summation of both conductivities is regarded as a conductivity of coolant region.

Table I: Several ETC models

Categorization	Model
Average model	- Chaudhary and Bhandari model $k_e = \left[(1-v_2)k_1 + v_2 k_2\right]^{f_{CB}} \times \left(\dfrac{1-v_2}{k_1}+\dfrac{v_2}{k_2}\right)^{(1-f_{CB})}$ - Weighted geometric mean model (WGGA model) $k_e = \left[(1-v_2)k_1 + v_2 k_2\right]^{f_{WGGA}} \times \left(k_1^{(1-v_2)}k_2^{v_2}\right)^{(1-f_{WGGA})}$
Maxwell - based model	- Hamilton's modification of the Maxwell-Eucken model $k_e = k_1\dfrac{k_1(1-v_2)+k_2(1+v_2)}{k_1(1+v_2)+k_2(1-v_2)}$
Others	- Tanaka-Chisaka model $\dfrac{k_e}{k_1} = (1-A)\dfrac{\log\left[1+B\left(\dfrac{k_2}{k_1}-1\right)\right]}{B\left(1-\dfrac{k_1}{k_2}\right)}+A$ where $A=\dfrac{2(1-v_2)}{2+v_2}$, $B=\dfrac{2(1-v_2)}{3}$

3. Evaluation of ETC models

To verify a suitability of each ETC model, CFD analysis and experiment were performed. Commercial CFD code, CFX-14 [5] was used for CFD analysis.

Computational domain was a cross-sectional geometry of the fuel block. For the experiment the test block was some part of the fuel block. The details are as follows.

3.1. Comparison with CFD analysis

For the CFD calculation, the computation domain consists of one fuel block and four 1/4-fuel blocks as shown in Fig. 1. Fuel gap that could exist between a fuel compact and graphite was not modeled. The conductivity of graphite was equal the properties of IG-110. The conductivity of helium was also set to temperature-dependent properties at 8 MPa. Steady-state and two-dimensional CFD simulations were performed with the energy conservation equation. RMS residual target for closure of energy conservation equation was set to 10^{-7}. To calculate radiation heat transfer, Discrete Transfer Radiation Model (DTRM) was employed.

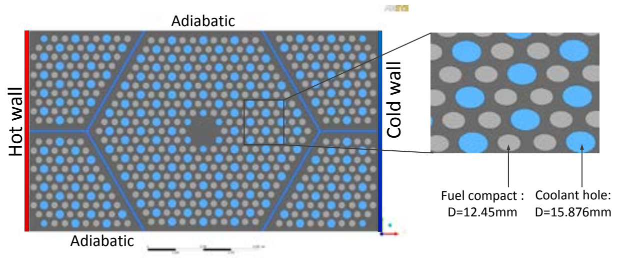

Fig. 1. Computational domain for CFD analysis

The results of the CFD calculations were compared to those of the ETC models. The WGGA model showed the least average difference from CFD result by 2.351%. And the second least difference, 4.287%, was shown in the CB model. However, these models have limitations that the physical explanation is missing and the model requires a weighting factor which is determined empirically.

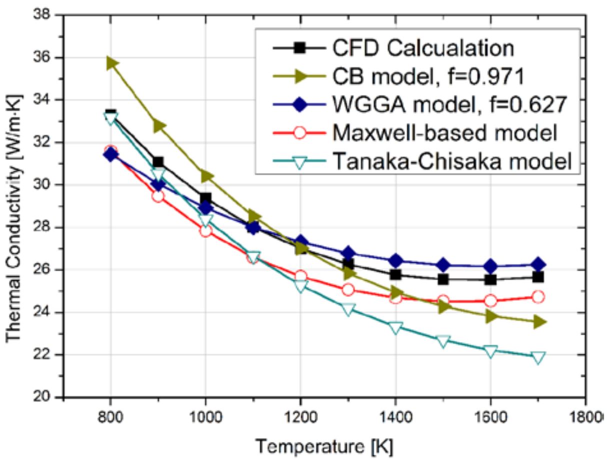

Fig. 2. Comparison of the CFD calculation and ETC models

And the difference between CFD calculation and the Tanaka-Chisaka model got larger with the increasing temperature. At the highest temperature, the Tanaka-Chisaka model showed the largest difference among the ETC models. Although the Maxwell-based model shows the difference of 4.585 %, the difference was not so large and the tendency of the model result was similar with that of the CFD calculation. Therefore it could be concluded that Maxwell-based model adopted in the GAMMA+ code is most proper model to predict an ETC of the fuel block.

3.2. ETC measurement experiment

An experiment was conducted to measure the ETC value of VHTR fuel block geometry. Test block was extracted from the fuel block and had same distribution of coolant holes and fuel holes with the prototype as shown in Fig. 3. Stainless steel rod was selected as the surrogate of fuel compact. One side of the test block was heated by the electrical heater and the opposite side was cooled. Using the heat flux and the temperature difference between the heating wall and the cooling wall, the ETC was obtained. Heat loss that could make some error in ETC value was reflected as uncertainties in error analysis.

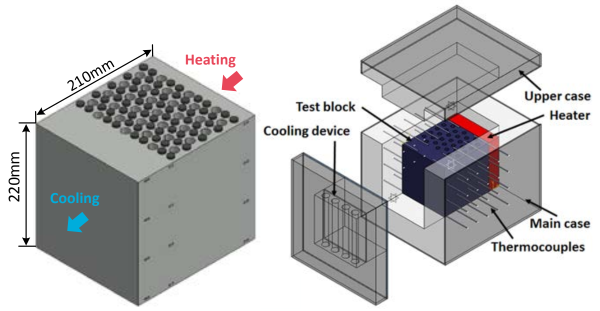

Fig. 3. Diagram of test block and experimental apparatus

The experimental results are compared to Maxwell-based model that is used in the GAMMA+ code. Compared to the result of the ETC model, the experimental result slightly under-predicted the ETC value. This is because there were gaps between stainless steel rod and graphite. The gaps encircling the rods could not be considered in the ETC model since the model uses only volume fractions and thermal conductivities without any geometric information. The volume fraction of gaps are relatively small, but the effect of the gaps as a thermal resistance is significant. The CFD calculation where the fuel gap was modeled showed similar result with the experimental result. In the real situation, however, the thermal conductivity of fuel compact is under 12 W/m·K that is about 1/5 to 1/10 of graphite conductivities. Therefore the heat transfer through the fuel compact is insignificant and the fuel gaps that might be exist between fuel compact and graphite rarely affect the ETC value of fuel block. [6]

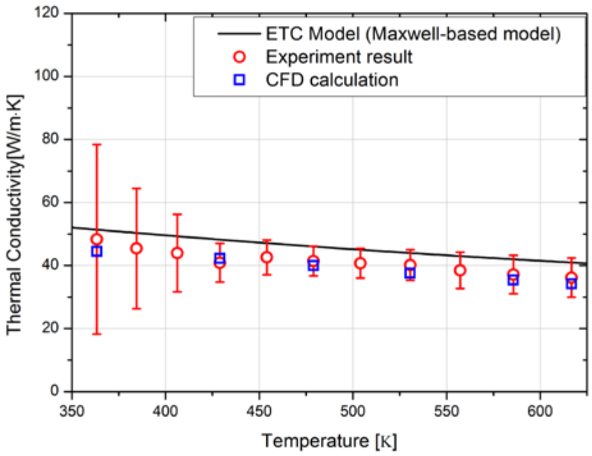

Fig. 4. Comparison of the experimental result and the ETC model result.

4. Conclusion

In this study, the ETC models were evaluated by comparison of CFD analysis and experimental results. The CFD analysis was conducted for the realistic fuel block geometries with various conditions. The Maxwell-based models showed good agreement with CFD calculation in terms of tendency and values. Although the average model showed small difference from CFD calculation, the weighting factor which should be determined empirically hinders its usefulness. The Maxwell-based model was also compared to the experiment result. The model could not include the fuel gap effect. But the effect is not significant in the real situation. Accordingly, the model is pertinent for the VHTR fuel block. However, the usage of the model calls for care when the effect of fuel gap is important or the thermal conductivity of fuel compact is relatively large.

Acknowledgement

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