Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

Assessment for the Applicability of Effective Thermal Conductivity Models on the Prismatic Fuel Assembly of Very High Temperature Reactor

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1. Introduction

A prismatic gas-cooled reactor is promising reactor type in the Nuclear Hydrogen Development and Demonstration (NHDD) project which was launched at KAERI (Korea Atomic Energy Research Institute) [1]. One of the most favorable characteristics of a prismatic gas-cooled reactor is its inherent and passive safety [2]. As one of its inherent safety features, the heat flows through the prismatic core radially during the High Pressure Conduction Cooling (HPCC) or Low Pressure Conduction Cooling (LPCC) event and the radial heat transfer cools down the reactor core passively under such conditions [1].

To verify the inherent safety of its design, the GAMMA+ code that is used to analyze VHTR thermo-fluid transients has been developed by KAERI [3]. The code adopts effective thermal conductivity (ETC) model to analyze radial heat transfer in the core as a lumped parameter model. It is because the fuel block has complex geometry with large number of coolant holes and fuel compacts and the detail heat transfer calculations on that geometry needs excessive computation resources. GAMMA+ is adopting the Maxwell-based ETC model, however, there are several ETC models that could be applied to the GAMMA+ code.

In this study, several ETC models will be introduced. They will be compared to CFD calculations which have similar condition with the fuel block. And then the most appropriate ETC model will be suggested for calculating the ETC of the fuel block.

For the CFD calculation, unit cell tests with simple geometries were conducted. With unit cell test, the applicability of the ETC models were investigated. And proper ETC models were used to calculate the ETC of the fuel block and the results were compared to that of CFD calculation on the fuel block.

2. Comparison between ETC models and CFD calculation

2.1 ETC Models

The ETC models that can be applied to the calculation for ETC of prismatic core are categorized into three types and the categorization is based on its assumption and theory. The first type is the averaged ETC model. The averaged ETC model contains harmonic mean model, arithmetic mean model, geometric model, and other mixed mean models. Another type is the Maxwell-based ETC model which theory was inferred from Maxwell's study on electrical conduction through the heterogeneous medium. The similarity of the governing equations between heat conduction and electrical conduction was employed. The GAMMA+ code adopts this type of ETC model. The other type is effective medium theory model. Effective Medium Theory (EMT) is a statistical approach that has often been used to model the conductivity of random mixtures of component materials [4]. Except for that, two additional models that are not included in the above categorization will be introduced; Russell ETC model and Tanaka & Chisaka model. The latter is used as the heat transfer model for HTGR core in MELCOR 2.1 [5].

2.2 CFD calculation

The aforementioned ETC models were evaluated by comparison with the analysis result of commercial code, CFX-13. CASE-1 was unit cell test to assess the applicability of ETC models to VHTR core heat transfer without regard to a radiation heat transfer. The calculation geometry was the 100mm square graphite block with 49 helium holes. The fraction of helium holes varies from 0.25 to 0.45 with the interval of 0.05. However, the radiation heat transfer play a major role in the radial heat transfer of fuel blocks. Therefore CASE-2 includes the radiation effect with different sizes of helium holes with the helium fraction of 0.45. Finally, ETC model is applied to fuel block geometry with realistic properties in CASE-3.

2.3 Comparison result

The applicability of the ETC models was investigated in CASE-1. The results of arithmetic mean and geometric mean showed large differences compared to those of CFD calculation because these models could not reflect the physical phenomena. Since the conductivity of helium is very low and the harmonic mean is strongly dependent on the lower one, the results of the harmonic mean model were near to zero. Therefore, the harmonic mean model is not appropriate for the heterogeneous material of which components have largely different conductivities. Similarly, Krischer model that is the weighted geometric mean of series model and parallel model was not suitable for that case. Chaudhary & Bhandari model was the only ETC model that shows reasonable result. The average difference between CFD calculation and Chaudhary & Bhandari model was 4.42%.

And then, the result of CFD calculation in CASE-1 was compared to that of Chaudhary & Bhandari model and other ETC models as shown in Fig. 1.

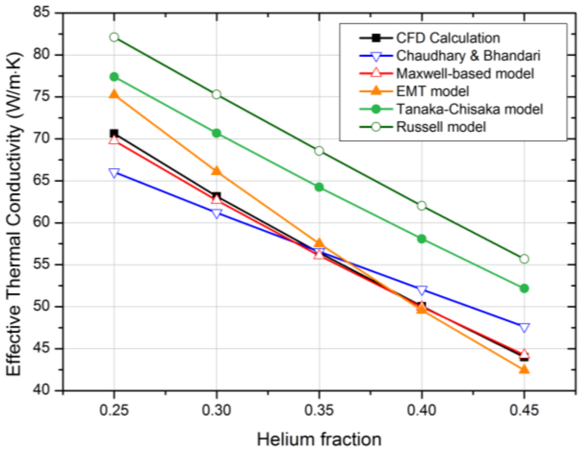

Fig. 1. Comparison of the CFD calculation and ETC models for the CASE-1

It is shown that the Tanaka-Chisaka model and the Russell model overestimates the ETC. It is because the geometric structure on which these models are based doesn't correspond to this calculations. While two-dimensional heat flow occured on the square domain containing helium holes for the CFD calculation, the Tanaka-Chisaka model was developed for packed bed and Russell model was for the continuous grid-like matrix. On the other hand, the geometry that Maxwell-based model considers as an object is cylindrical holes embedded in large domain, which is similar to this calculation geometry. As a result, Maxwell-based model showed the least difference of 0.68% from CFD calculation. Though the EMT model is analogous to Maxwell-based model, it has a contrast to Maxwell-based model in the point that it does not distinguish the continuous phase and dispersed phase. The EMT model has the second least difference of 3.51% from CFD calculation.

In CASE-2, the effect of radiation heat transfer was investigated by adding the equivalent radiation conductivity to the gas conductivity. The EMT model is not shown on the Fig. 2 since it yielded large ETC values which was out of range of graphite conductivity. The EMT model is so sensitive to the conductivity of dispersed phase that small increase of gas conductivity makes significantly large increase of ETC. The results of other models are shown in Fig. 2.

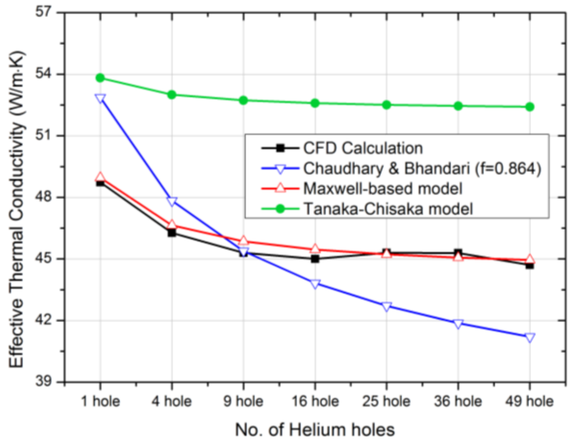

Fig. 2. Comparison of the CFD calculation and ETC models for the CASE-2

Fig. 2. shows that the Tanaka-Chisaka model still overestimates the ETC. Chaudhary & Bhandari model has 5.10% of the average difference from CFD calculation. By contrast, the results of Maxwell-based model are very similar to the CFD calculation, as it shows 0.67% of the average difference. It is indicated that the effect of radiation heat transfer was reflected properly in the Maxwell-based model.

In CASE-3, CFD calculations were conducted with fuel block geometry. The Maxwell-based model which was the most proper ETC models in CASE-1 and CASE-2 was compared to CFD calculation.

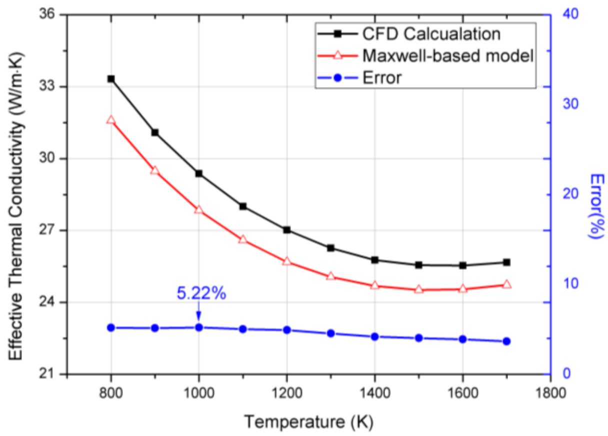

Fig. 3. Comparison of the CFD calculation and Maxwell-based model (CASE-3)

The tendency and values of the Maxwell-based model are close to those of CFD calculations. The maximum difference between them was 5.22%. It could be concluded that Maxwell-based model is the most appropriate model for obtaining the ETC of fuel block.

3. Conclusions

In this study, the ETC models are introduced and the applicability of the ETC models to VHTR fuel block was investigated. The results of the ETC models were compared to those of CFD calculation. The CFD calculations were conducted for square graphite block and fuel block geometry. Using the square block, the unit cell tests were conducted and basic properties of the ETC models were identified. In the averaged ETC models, the Chaudhary and Bhandari model was the solely available ETC model. However, Chaudhary and Bhandari model showed larger differences from CFD calculations than Maxwell-based model in CASE-2. The EMT model showed good agreement with CFD calculation in CASE-1, while the model yielded much higher ETC values than CFD calculation in CASE-2. It is because the EMT model is so sensitive to the conductivity of dispersed phase that it could not reflect the effect of radiation heat transfer properly. The Tanaka-Chisaka model and the Russell model constantly overpredicted the ETC values. Otherwise, the results of the Maxwell-based model showed good agreement with CFD calculation in all cases. It could be concluded that the Maxwell-based model is the most pertinent ETC model for the fuel block

Acknowledgements

This study was supported in part by Nuclear Hydrogen Development and Demonstration (NHDD) Project coordinated by Korea Atomic Energy Research Institute. (NRF-2014M2A8A2021297).

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