EXPERIMENTAL STUDY ON THE MEASUREMENT OF EFFECTIVE THERMAL CONDUCTIVITY FOR VHTR FUEL BLOCK GEOMETRY

Dong-Ho Shin[1], Hyoung-Kyu Cho[1]*, Nam-Il Tak[2] and Goon-Cherl Park[1]
[1]Department of Nuclear Engineering, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, Rep. of Korea
[2]Korea Atomic Energy Research Institute, Daedeok-daero 989-11, Yuseong-Gu, Daejeon, Republic of Korea
E-mail: chohk@snu.ac.kr

ABSTRACT

Effective thermal conductivity models which can be used to analyze the heat transfer phenomena of a prismatic fuel block were evaluated by the experiments. In the accident condition of VHTR when forced convection is lost, the heat flows in radial direction through the hexagonal fuel blocks that contain the large number of coolant holes and fuel compacts. Due to the complex geometry of fuel block and radiation heat transfer, the detail computation of heat transfer on the fuel block needs excessive computation resources. Therefore, the detail computation isn't appropriate for the lumped parameter code and a system code such as GAMMA+ adopts effective thermal conductivity model. Despite the complexity in heat transfer modes, the accurate analysis on the heat transfer in fuel block is necessary since it is directly relevant to the integrity of nuclear fuel embedded in fuel block. To satisfy the accurate analysis of complex heat transfer modes with limited computing sources, the credible effective thermal conductivity (ETC) models in which the effects of all of heat transfer modes are lumped is necessary. In this study, various ETC models were evaluated with the experiment result. Experiments for measuring the ETC values of the VHTR fuel block geometry were conducted with IG-11 graphite block. And four probable models compared to the experiment result showed good agreement with them, and thus they could be a candidate ETC model for VHTR fuel block.

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, 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 in high pressure or low pressure, the core is heated by the decay heat and then cooled down by conduction and radiation to the Reactor Cavity Cooling System across the prismatic core [2]. The fuel block included in the core is hexagonal prism shape and 800 mm in height. It contains 108 cylindrical coolant holes and 210 cylindrical fuel compacts as shown in **Figure 1**. In VHTR, helium passes through the cylindrical coolant channel in the fuel block as a coolant, and the fuel hole that has the diameter of 12.7 mm contains cylindrical fuel compact of which diameter is 12.45 mm. 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 an Effective Thermal Conductivity (ETC) model is adopted for calculating the thermal distribution of the VHTR core in the lumped parameter code such as the GAMMA+ code [4] which is developed for an analysis of thermal-hydraulics and the safety of VHTR by Korea Atomic Energy Research Institute. The ETC model regards a fuel block including lots of coolant holes and fuel compacts as a single homogenized medium with a single property. Since the ETC of the fuel block is closely relative to the core peak temperature and the safety of the reactor, the validation of the ETC model is required.

In this study, several effective thermal conductivity models were suggested and validated by experiments. The test blocks

NOMENCLATURE

k	[W/mK]	Thermal conductivity
T	[K]	Temperature
v	[-]	Volume fraction
q	[W/m^2]	Heat flux
d_{12}	[m]	Distance between plane1 and plane2
d_{23}	[m]	Distance between plane2 and plane3
U	[-]	Uncertainty
B	[-]	Bias error
Special characters		
σ	[W/m^{-2}K^{-4}]	Stefan-Boltzmann constant
δ	[-]	Average distance between two opposite plane
Subscripts		
avg		Average
eff		Effective
$loss$		Heat loss
max		Maximum
r		Radiation
1		Composite material 1
2		Composite material 2

used in the experiments were composed of IG-11 graphite that is a material of VHTR fuel block and have same geometry with its fuel block. The experimental data were compared to the results of the ETC models.

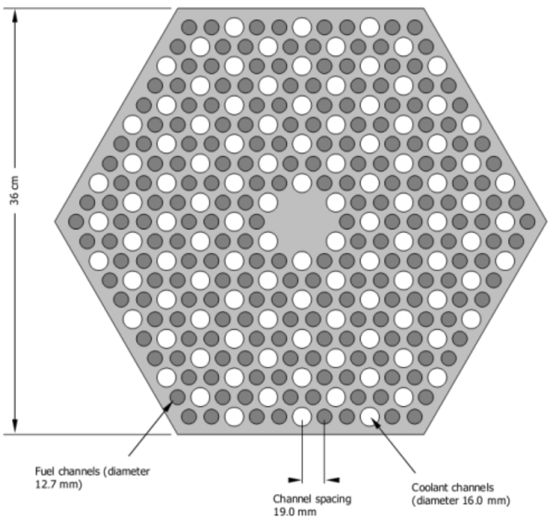


Figure 1 Cross-sectional view of VHTR fuel block [3]

EFFECTIVE THERMAL CONDUCTIVITY MODEL

Using the thermal conductivity and volume fraction of each material, ETC model gives homogenized thermal conductivity of heterogeneous material when each component is mixed randomly. The effects of heat transfer modes including gas conduction, solid conduction and radiation are lumped in the ETC. For the radiation heat transfer, it is reflected in the form of an equivalent radiation heat transfer conductivity that is obtained as follows;

$$k_r = 4F\sigma\delta\overline{T}^3 \qquad (1)$$

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 gas region.

However, the overall or average conductivity of a composite medium depends strongly on the morphology of the medium. And there is presently no general solution to the problem of determining the overall conductivity of a composite medium of arbitrary morphology [5]. Therefore the adoption of appropriate ETC model should be paid close attention and requires a validation.

There are several ETC models that can be applied to the VHTR fuel block. They can be divided into three types; the averaged ETC model, the Maxwell-based model, and the EMT model. And there are other two models – Russell model and Tanaka-Chisaka model – that are not included in the categorization. The averaged ETC model contains harmonic mean model, arithmetic mean model, geometric model, and other mixed mean models such as the weighted geometric mean model. The Maxwell-based ETC model was derived from Maxwell's study on electrical conduction through the heterogeneous medium and the similarity of the governing equations between heat conduction and electrical conduction was employed. The GAMMA+ code adopts this ETC model for the VHTR fuel block. Effective Medium Theory (EMT) is a statistical approach that has often been used to model the conductivity of random mixtures of component materials [6]. The Tanaka-Chisaka model is used as the heat transfer model for HTGR core in MELCOR 2.1 [7].

In the previous study [8], several ETC models were reviewed and validated by CFD analysis. Among them, 4 models that were the most probable for the ETC model of VHTR fuel block was compared to the experimental results in this study. The form of each model is as shown in Table I.

Table 1. ETC models

Categorization	Model
Average model	- Chaudhary and Bhandari (CB) model $k_{eff} = \left[(1-v_2)k_1 + v_2k_2\right]^{f_{CB}} \times \left(\dfrac{1-v_2}{k_1} + \dfrac{v_2}{k_2}\right)^{(f_{CB}-1)}$ - Weighted geometric mean (WGGA) model $k_{eff} = \left[(1-v_2)k_1 + v_2k_2\right]^{f_{WGGA}} \times \left(k_1^{(1-v_2)}k_2^{v_2}\right)^{(1-f_{WGGA})}$
Maxwell - based model	- Hamilton's modification of the Maxwell-Eucken model $k_{eff} = k_1\dfrac{k_1(1-v_2)+k_2(1+v_2)}{k_1(1+v_2)+k_2(1-v_2)}$
Others	- Tanaka-Chisaka model $\dfrac{k_{eff}}{k_1} = (1-A)\dfrac{\log\left[1+B\left(\dfrac{k_2}{k_1}-1\right)\right]}{B\left(1-\dfrac{k_1}{k_2}\right)} + A$ where $A = \dfrac{2(1-v_2)}{2+v_2}$, $B = \dfrac{2(1-v_2)}{3}$

EXPERIMENTAL APPARATUS AND METHOD

An experiment was conducted to measure the ETC value of VHTR fuel block geometry. The geometry of the test block was designed to have a same distribution of coolant holes and fuel holes with the prototype as shown in **Figure 2**. Test block was composed of IG11 graphite that is the material of the VHTR fuel block and structure. Stainless steel rod was selected as the surrogate of the fuel compact. One side of the test block was heated by the electrical heater and the opposite side was cooled by a cooling block where the water channel was buried. Using the heat flux and the temperature difference through the test block, the ETC was obtained.

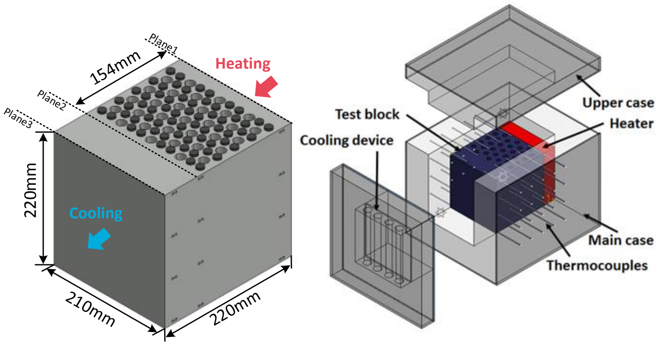


Figure 2 Diagram of test block and experimental apparatus

The test block is divided into two sections. The first section between Plane 1 and Plane 2 in the Figure 2 is the region where the ETC is obtained, and the second region between Plane 2 and Plane 3 in the Figure 2 is to obtain the heat flux. To obtain a temperature difference inside the first section of test block, the average temperatures of two planes are measured. At each plane, the 16 temperatures of the evenly distributed points were measured and they were used to calculate the average temperature of that plane. To measure the temperature on the plane inside the block, thermocouples were inserted through the side wall. Heat fluxes were calculated between plane 2 and plane 3 using temperature differences and thermal conductivity of IG-11 graphite as follows;

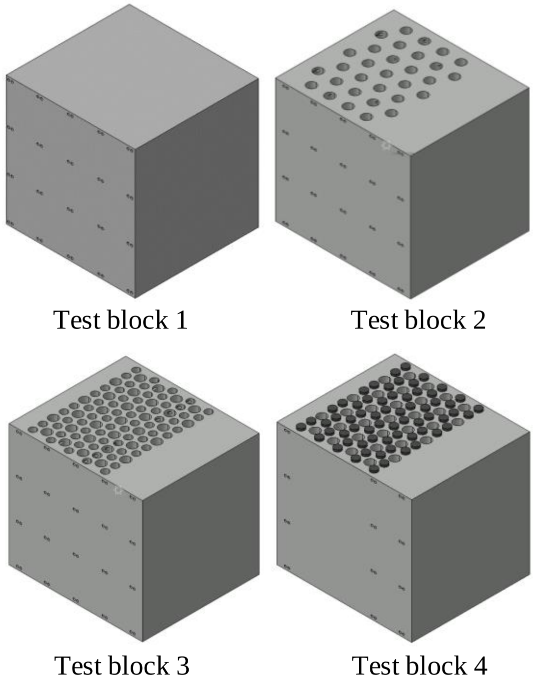
$$q = k_{IG11}\left(T_{avg}\right)\frac{\sum_{i=1}^{16} T_{i,plane2} - \sum_{i=1}^{16} T_{i,plane3}}{16\, d_{23}}. \qquad (2)$$

And the ETC of the test block is determined by the Fourier's law as follows.

$$k_{eff} = q\frac{16\, d_{12}}{\sum_{i=1}^{16} T_{i,Plane1} - \sum_{i=1}^{16} T_{i,Plane2}} \qquad (3)$$

Since a one-dimensional heat flow was assumed in acquiring the ETC, heat loss could make some error in heat flux values, which lead to error in the ETC. Therefore, heat loss was reflected as uncertainties in error analysis.

Four kinds of test blocks were used in the experiment as shown in **Figure 3**. Test block 1 was IG-11 graphite block with no void, so that the experiment method could be verified. Test block 2 had 31 coolant holes with 0.19 of void fraction and Test block 3 had not only coolant holes but also 64 fuel holes with 0.43 of void fraction. In the test block 4, the stainless rods were inserted in the fuel holes as surrogates of the fuel compact. ETC values measured from Test block 4 represented that of the VHTR fuel block.


Test block 1

Test block 2

Test block 3

Test block 4

Figure 3 Diagram of 4 test blocks

RESULT AND ERROR ANALYSIS

Before the result being discussed, the error in the experiments was assessed considering uncertainties of thermocouples and heat loss. In addition, uncertainties due to material properties which were used for obtaining heat flux were considered. The uncertainties of thermocouples below 200 °C were measured using thermal bath and those of thermocouples above 200°C was ±1.5°C that was provided by the manufacturer.

Equation (3) shows that ETC values from the experiment is the function of heat flux and temperatures as bellows.

$$k_{eff} = f\left(q, T_{1,plane1}, \cdots, T_{16,plane1}, T_{1,plane2}, \cdots, T_{16,plane2}\right) \quad (4)$$

Uncertainties of the heat flux and temperatures were propagated to the ETC value. Using the Taylor series method for propagation of uncertainties, the uncertainties of ETC value is given by:

$$U_{k_{eff}}^2 = \left(\frac{\partial k_{eff}}{\partial q}\right)^2 U_q^2 + \sum_{i=1}^{16}\left(\frac{\partial k_{eff}}{\partial T_{i,plane1}}\right)^2 U_{T_{i,plane1}}^2 + \sum_{i=1}^{16}\left(\frac{\partial k_{eff}}{\partial T_{i,plane4}}\right)^2 U_{T_{i,plane4}}^2 \; . \quad (5)$$

Although each temperature on the measurement plane has different uncertainty with others, the representative uncertainty which is the largest one among temperatures of the plane, is adopted because the differences among them are not so much. Taking the derivatives of ETC value with respect to the temperatures, using the representative uncertainties, and then dividing by k_{eff}^2, Equation (5) could be simplified as below.

$$\frac{U_{k_{eff}}^2}{k_{eff}^2} = \left(\frac{U_q}{q}\right)^2 + \frac{16\left(U_{T_{\max,plane4}}^2 + U_{T_{\max,plane1}}^2\right)}{\left(\sum_{i=1}^{16} T_{i,plane1} - \sum_{i=1}^{16} T_{i,plane4}\right)^2} \quad (6)$$

And the above equation also requires the uncertainty of the heat flux. Since the heat flux is not directly measured value but calculated value, the uncertainty of the heat flux should be evaluated. Similarly, Taylor series method for uncertainties propagation of the heat flux gives:

$$\frac{U_q^2}{q^2} = \left(\frac{U_{k_{IG11}}}{k_{IG11}}\right)^2 + \frac{k_{IG11}^2}{q^2}\left(\frac{U_{T_{\max,plane4}}^2 + U_{T_{\max,plane5}}^2}{16\, d_{23}^2}\right) + B_{loss}^2 \; . \quad (7)$$

It is noticed that the heat loss assessed by the difference between input power and measure heat flux is included in the uncertainties of heat flux as a bias error. All of uncertainties of the experimental results were evaluated in this manner.

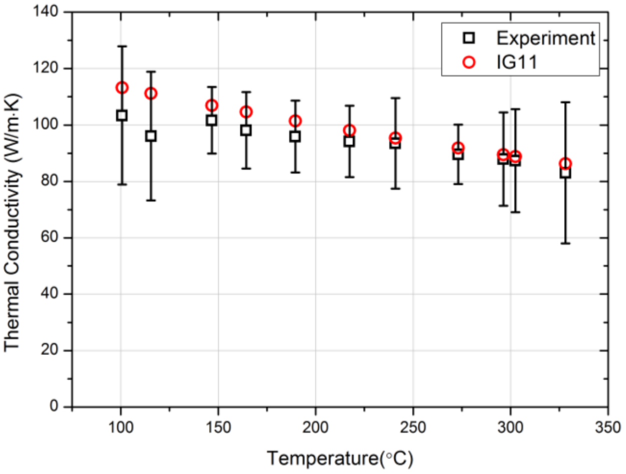


Figure 4 Experimental result with IG-11 properties (Test block 1)

First, the experimental method was validated with Test block 1. Test block 1 is composed of IG-11 graphite and thus the thermal conductivities that were measured in the experiment should be consistent with the properties of IG-11 if the experimental result was valid. The result with Test block 1 is shown in **Figure 4**. Although the error bar of experiment was relatively large, the IG-11 properties were included in the error range of the experimental results. It could be concluded that the experimental method was suitable

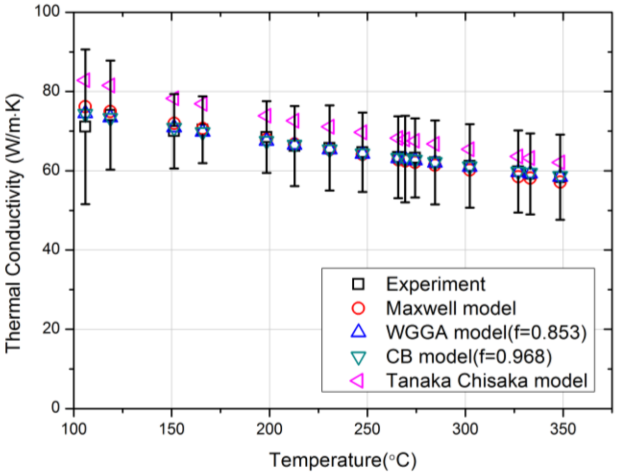


Figure 5 Experimental results with the results of ETC models (Test block 2)

And then the experimental results were compared to the results from the ETC models presented in Table 1. In the experiment with Test block 2 and Test block 3, all of the results from the ETC models agreed well with experimental data as shown in **Figure 5**. Though the Tanaka-Chisaka model showed a little higher results compared to experimental results by 9.8% in average difference, they were also included in the error range. The WGGA model and CB model require the weighting factor that should be determined empirically, however, they could express the experimental result very well if the appropriate weighting factor is selected.

Figure 6 shows the experimental results from Test block 4. Test block 4 contains stainless steel rods as fuel block surrogates. Compared to the results of the Maxwell model and Tanaka-Chisaka model, the experimental result shows slightly lower ETC value by 11.6% and 14.8% respectively. 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. In contrast, the average models – WGGA model and CB model – corresponded well to the experiment result, since the adjustment of the weighting factor made them accord to the experiment result.

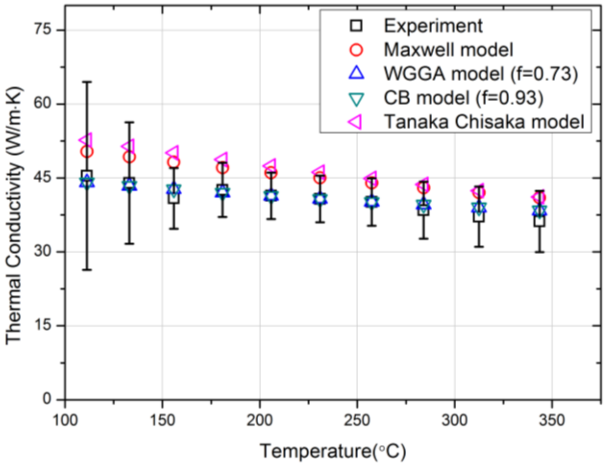


Figure 6 Experimental results with the results of ETC models (Test block 4)

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.

CONCLUSION

In this study, the ETC models were introduced and evaluated by comparison of experimental results. The effective thermal conductivity was measured by one-dimensional heat conduction equation method. Test block was composed of IG-11 graphite with cylindrical coolant hole and fuel compact. All models compared to the experimental results showed good agreement with them. In Test block 4 including stainless steel rods as surrogates of fuel compact, however, the Maxwell model and Tanaka-Chisaka model overpredicted ETC value. Those two model have a physical basis but the fuel gap which deteriorates the thermal conductivity could not be considered in the ETC models. In contrast, the average models – WGGA model and CB model – corresponded well to the experiment results, though they don't have physical basis but require an empirically determined weighting factor. In real situation, the fuel gap effect doesn't seem to be significant due to low thermal conductivity of fuel compact. Therefore four models compared to the experiment results in this study could be a candidate ETC model for VHTR fuel block geometry. But in the temperature range where the experiments were conduct, the effect of radiation heat transfer is not obvious. So additional research on its effect is required.

ACKNOWLEDGEMENT

This research was supported by the National Nuclear R&D Program through the National Research Foundation of Korea(NRF) funded by MSIP; Ministry of Science ICT & Future Planning (No. NRF-2014M2A8A2074314)

REFERENCES

[1] Jun J.S., Thermal–Hydraulic Analysis of PMR 200MWth Demonstration Reactor Candidate Core using GAMMA+ Code, KAERI, *NHDD-RD-CA-09-004*, 2009

[2] Chang J. H., Kim Y. W., Lee K. Y., et al., A study of a nuclear hydrogen production demonstration plant, *Nuclear Engineering and Technology*, Vol. 39, p. 111, 2007

[3] Stainsby R., et al., Investigation of Local Heat Transfer Phenomena in a Prismatic Modular Reactor Core, *AMEC Report NR001/RP/001 R02*, 2009

[4] Lim H. S., Transient Gas Multicomponent Mixture Analysis Code for Analyzing the Thermo-Fluid Transients in a VHTR; Vol. II GAMMA+ Theory Manual, KAERI, *NHDD-RD-CA-13-006*, 2013.

[5] Davis H. T. Valencourt, L.R. Johnson, C.E., Transport Process in Composite Media, *Journal of the American Ceramic Society*, Vol. 58, 1975, pp. 446-452,

[6] James K Carson, Prediction of the Thermal Conductivity of Porous Foods, Massey University, Palmerston North, 2002

[7] Seoung-Su Jeon, et. al., MELCOR Simulation on Steady-State and D-LOFC of HTGR with RCCS, *Transactions of the KNS spring meeting*, Jeju, Rep. of Korea, May 2014

[8] Shin D. H., et al., Evaluation of Effective thermal conductivity models on the prismatic fuel block of a Very High Temperature Reactor by CFD analysis, *Proceedings of the HTR 2014*, Weihai, China, October 2014

[9] Shin D.H., et al., Analytical Study on the Effective Thermal Conductivity of VHTR Fuel Block Geometry with Multiple Cylindrical Holes. *Nuclear Technology*, 2015 (Submitted in 2014).