Validation of GAMMA+ model for Evaluating Heat Transfer of VHTR core in Accident Conditions by CFD analysis

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1. Introduction

The Very High Temperature gas-cooled Reactor (VHTR) is expected to play a major role in hydrogen economy as a cheap and massive hydrogen source [1]. In Korea, the Nuclear Hydrogen Development and Demonstration (NHDD) project has been launched at KAERI (Korea Atomic Energy Research Institute). KAERI has established a plan to demonstrate massive production of hydrogen using a VHTR by the early 2020s [2]. In addition the GAMMA+ code [3] is developed to analyze VHTR thermo-fluid transients at KAERI.

One of the candidate reactor designs for VHTR is prismatic modular reactor (PMR), of which reference reactor is the 600MWth GT-MHR. This type of reactor has a passive safety system. During the High Pressure Conduction Cooling (HPCC) or Low Pressure Conduction Cooling (LPCC) accident, the core heats up by decay heat and then starts to cool down by conduction and radiation cooling to the Reactor Cavity Cooling System (RCCS) through the prismatic core [2]. In this mechanism, the solid conduction occurs in graphite and fuel blocks, and the gas conduction and radiation occurs in coolant holes and bypass gaps. It is important to predict conduction and radiation heat transfer in the core for safety analysis.

The GAMMA+ code adopts effective thermal conductivity (ETC) model to analyze these heat transfer phenomena. In this model, heterogeneous medium is homogenized with effective thermal conductivity. Effective thermal conductivity is derived by Maxwell's far-field methodology Radiation effect is expressed as corresponding conductivity and added to gas conductivity. In this study, ETC model used in GAMMA+ code is validated with the commercial CFD code, CFX-13 [4].

2. Comparison of GAMMA+ model and CFD analysis

2.1 GAMMA+ Model

GAMMA+ model consists of three parts. Radiation heat transfer model [5] gives equivalent radiation conductivity, which is added to gas conductivity to produce net conductivity of coolant hole. And this coolant hole conductivity and graphite conductivity is homogenized to effective thermal conductivity by effective thermal conductivity model. At last, the effect of bypass gap is added to effective thermal conductivity of graphite block by bypass gap model [5]. Each model is as follows:

1) Effective thermal conductivity model

$$k_{eff} = k_{out} \frac{1 - \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)}{1 + \sum_{i=1}^{N} \alpha_i \left(\frac{k_{out} - k_i}{k_{out} + k_i} \right)} \qquad (1)$$

2) Radiation heat transfer model

$$k_r = 4F\sigma\delta\overline{T}^3 \qquad (2)$$

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

3) Bypass gap model

$$\overline{k}_{gap} = k_r + k_{gas} = 4F\sigma T^3(0.5\delta_{gap}) + k_{gas} \qquad (3)$$

And bypass gap is considered as a series of thermal resistances. The effective conductivity of graphite block and bypass gap is eventually combined as follows;

$$\frac{\delta_{total}}{k_{total}} = \frac{\delta_{block}}{k_{block}} + \frac{0.5\delta_{gap}}{k_{gap}}. \qquad (4)$$

2.2 Comparison of GAMMA+ model with CFD analysis

The effective thermal conductivity model of the GAMMA+ code was evaluated by comparing with the commercial code, CFX-13, analysis result. Three different cases were tested; CASE-1 was the effective thermal conductivity variation depending on the number of holes with same coolant volume fraction, CASE-2 was simulated with the 49-hole blocks with different coolant volume fractions, and CASE-3 was to compare the model and the CFD code results depending on temperature variation.

The geometry dependency of the GAMMA+ model was investigated in CASE-1. The seven cubic graphite blocks with different numbers of the holes from 1 hole to 49 holes (1, 4, 9, 16, 25, 36, 49) were modeled as the test geometries. The boundary condition of this analysis was the heat flux of the heating wall and the imposed heat fluxes were 10kW, 50kW, and 100kW. A total of 21 runs were conducted in CASE-1. With the increasing heat flux and decreasing number of holes, the effective thermal conductivity was increased. It is caused by the increasing effect of the radiation heat transfer which is proportional to the diameter of a hole and the cube of the temperature as shown in Eq. (2). Though there are a few points where the discrepancies are noticeable, the predicted values by the GAMMA+ model agreed fairly well with the CFD code in general. Especially, the differences decreased with increasing number of holes because the assumption employed for the GAMMA+ model, which assumes an even spatial distribution of particles, becomes more valid with larger number and smaller size of the holes.

For CASE-2, the 49-hole block was used for the test geometry. As the volume fraction of coolant hole increases, the effective thermal conductivity decreases since the volume fraction of coolant hole, which has much lower thermal conductivity that the graphite block, increases. It is noted that the GAMMA+ model predicts effective thermal conductivity reasonably well in the wide range of coolant volume fraction.

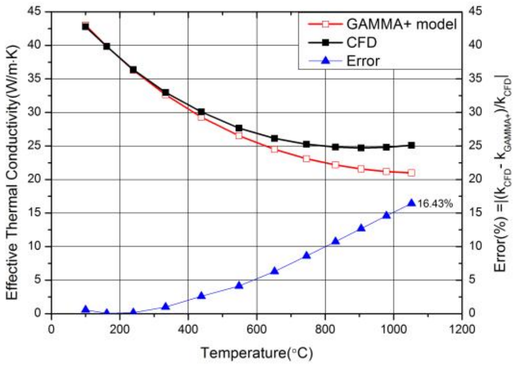

Fig.1. Comparison of the GAMMA+ model and CFD code depending on temperature (CASE-3)

Fig.1 shows that effective thermal conductivity profile depending on the temperature. The test geometry was 9-hole block. In the low temperature region below 500°C, the GAMMA+ model and CFD model showed a similar tendency. In high temperature region above 500°C, however, the difference between two results is enlarged as the temperature increases. Since the effect of radiation heat transfer increases exponentially with the temperature, the decreasing trend of the effective thermal conductivity predicted by CFD analysis is decelerated as temperature rises. However, the GAMMA+ model is probable to underestimate the effect of radiation heat transfer and, therefore, the model may underpredict the effective thermal conductivity. The radiation heat transfer of the GAMMA+ model is based on rather simple assumption, which is applicable for limited conditions; this deficiency is likely to be caused. More reviews and assessments for it are necessary in order to improve the predictability of the model in high temperature conditions.

3. Conclusions

In this study, the effective thermal conductivity model of the GAMMA+ was evaluated by comparison of CFD analysis. The CFD analysis was conducted for various numbers and volume fractions of coolant holes and temperatures. Although slight disagreement was shown for the cases run with small number of holes, the result of GAMMA+ model is accurate for the large numbers of holes sufficiently. Since there are 102 coolant holes and 210 fuel holes in a fuel block, it is concluded that GAMMA+ model is proper formula for predicting effective thermal conductivity of the VHTR fuel block. However, in high temperature region above 500℃, the GAMMA+ model underestimates the effective thermal conductivity since radiation heat transfer is not reflected precisely. Further researches on it seem to be necessary.

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