Evaluation of Thermal Conductivity of TRISO Fuel using CFD Code

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1. Introduction

The High-Temperature Gas-cooled Reactor (HTGR) concept was proposed at the Harwell Laboratory in the United Kingdom in the mid-1950s. The metallic cladding materials used in conventional light water reactors and fast reactors limit the cladding temperature to below 650°C, and therefore restrict raising the coolant outlet temperature above 600°C. A new fuel form capable of sealing the nuclear fuel under such high-temperature conditions was required, and the Harwell Laboratory developed a coated particle fuel in 1956 [1]. Coated particle fuel has since been developed over a long period, and by employing multilayer ceramic coatings it can retain fission products inside the fuel even at temperatures exceeding 1,000°C.

TRISO (Tri-structural Isotropic) fuel is a representative coated particle fuel applied to HTGRs and Heat Pipe-cooled Reactors (HPRs). TRISO fuel consists of fine spherical particles smaller than 1 mm, in which a porous pyrolytic carbon buffer layer, an inner pyrolytic carbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer pyrolytic carbon (OPyC) layer are formed around a fuel kernel. TRISO particles can be fabricated either into spherical graphite pebbles of approximately 6 cm in diameter or into small cylindrical compacts, which are applied to pebble-bed reactors and prismatic reactors, respectively. In both cases, the TRISO particles are dispersed within a graphite or silicon carbide matrix [2].

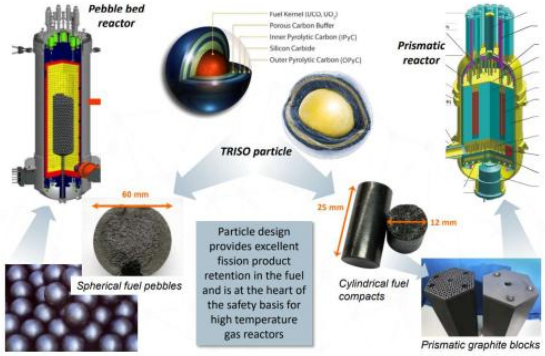


Fig. 1. Use of TRISO particles in reactor fuel forms: cylindrical compacts and spherical pebbles containing embedded TRISO particles [2].

Since TRISO fuel has a heterogeneous structure in which multilayer coatings and a matrix are combined, the heat transfer analysis of the fuel compact is complicated. In particular, for a structure in which TRISO particles are dispersed within a matrix, it is important to accurately predict the effective thermal conductivity (ETC) of the entire fuel compact. The ETC is used as a key parameter representing the heat transfer characteristics by which the heat generated in the fuel kernel is transferred to the outside through the successive coating layers and the matrix.

In previous studies, various numerical models have been used to analyze the heat transfer characteristics of TRISO fuel compacts. As shown in Fig. 2, representative heat conduction models can be classified into the multi-region layer (ML) model, the multi-region non-layer (MN) model, and the homogeneous model [3]. The ML model constructs all the coating layers of a TRISO particle directly, whereas the MN model simplifies each TRISO particle into a single homogeneous region. In the homogeneous model, the entire fuel compact including the TRISO particles and the matrix is treated as a single homogeneous region [3].

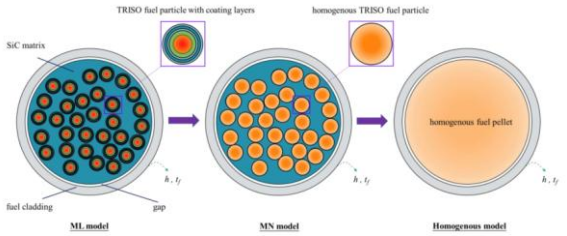


Fig. 2. Thermal conduction models on TRISO-embedded fuel [3].

In this study, CFD analysis results obtained using STAR-CCM+ were directly compared with existing experimental results in order to evaluate the predicted effective thermal conductivity of a TRISO fuel compact. For this purpose, the modeling was performed using the MN model approach, and among previous numerical studies the experimental data of Folsom et al. were selected as the object of comparison for the CFD model[4]. Folsom et al. measured the temperature-dependent ETC for four TRISO fuel compact specimens having the same packing fraction using the guarded-comparative-heat-flow technique, and compared the results with values calculated by the correlations of previous studies for the condition in which TRISO particles are distributed in a German A3-27 matrix at a volume fraction of 47.7% [4]. In the present study, these experimental conditions were applied to the STAR-CCM+ model, and the ETC was

calculated from the temperature gradient obtained in the CFD analysis and then compared with the experimental values.

2. CFD Model Development

A CFD model was constructed to evaluate the ETC of a TRISO fuel compact on the basis of the experimental conditions of Folsom et al. [4]. Fig. 3 shows a schematic of the guarded-comparative heat flow technique used in the experiment. In the experiment, reference materials of known thermal conductivity were placed on both sides of the specimen and heat was transferred in one direction, and the ETC was measured using the axial temperature gradient of the specimen.

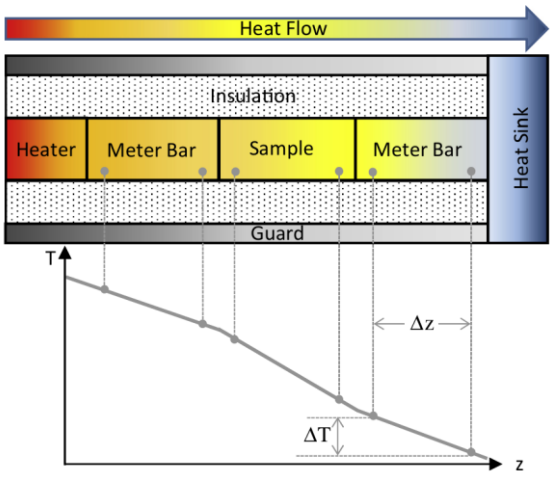


Fig. 3. Configuration diagram of the guarded-comparative heat flow apparatus applied to surrogate TRISO fuel compact measurements [4].

In the CFD analysis, only the TRISO fuel compact specimen was modeled rather than the entire experimental apparatus. A heat flux boundary condition was applied from the left to the right side of the specimen, and the lateral surface of the specimen was set as an adiabatic condition. As in the experiment, the effective thermal conductivity was evaluated using the axial temperature gradient of the specimen.

Fig. 4 shows the mesh of the TRISO particles-embedded fuel compact used in the CFD analysis. The diameter of the fuel compact is 12.4 mm and its height is 30 mm, and the diameter of the TRISO particles contained inside is 920 μm. The volume fraction of the TRISO particles was set to approximately 47.7%, and a thermal conductivity of 4.13 $W \cdot m^{-1} \cdot K^{-1}$ was applied to the TRISO particles [4]. Fig. 4(a) shows the three-dimensional mesh of the fuel compact containing the TRISO particles, and Fig. 4(b) shows the two-dimensional cross-sectional mesh.

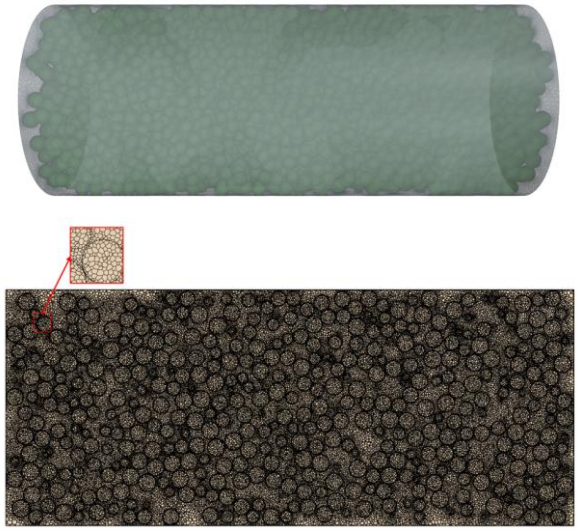


Fig. 4. Computational mesh generated for the TRISO particle-containing fuel compact: (a) 3-D mesh, (b) 2-D mesh.

Using the constructed model, heat conduction analyses were carried out at 100°C, 300°C and 500°C. Fig. 5 representatively shows the temperature distribution of the fuel compact obtained at the 500°C condition among the three conditions. As a result of applying the heat flux from left to right, the temperature difference between the left and right surfaces was calculated to be approximately 37.3°C, 44°C and 52°C at the 100°C, 300°C and 500°C conditions, respectively.

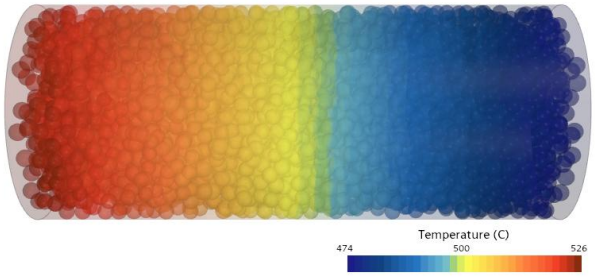


Fig. 5. Predicted temperature field within the TRISO fuel compact.

The ETC of the fuel compact at each temperature condition was calculated using the temperature gradient obtained from the CFD analysis. In Fig. 6, these CFD results are compared with the experimental results of Folsom et al. Folsom et al. measured the temperature-dependent ETC for four TRISO fuel compact specimens having the same packing fraction [4]. The four curves in Fig. 6 represent the experimental results of each specimen, and the triangular symbols marked at 100°C, 300°C and 500°C represent the ETC obtained from the CFD analysis of the present study.

As a result of the comparison, the ETC calculated by CFD was located within the measurement range of the four experimental specimens, and showed a result similar to the average variation trend of the experimental values with temperature. Therefore, it was

confirmed that the STAR-CCM+ CFD analysis results reproducing the experimental conditions of Folsom et al. show a reasonable agreement with the corresponding experimental data.

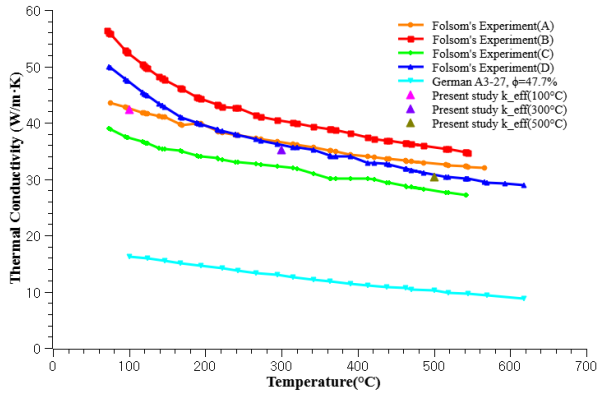


Fig. 6. Comparison between experimental and CFD-predicted effective thermal conductivity of TRISO fuel compacts at different temperatures.

3. Conclusion

In this study, CFD analysis using STAR-CCM+ was performed to evaluate the effective thermal conductivity (ETC) of a TRISO fuel compact, and the results were directly compared with the existing experimental results of Folsom et al. The MN (multi-region non-layer) model approach was applied, and the experimental conditions of Folsom et al. were identically implemented in the CFD model, with heat conduction analyses carried out at 100°C, 300°C and 500°C.

As a result of the analysis, the temperature difference between the left and right surfaces was calculated to be approximately 37.3°C, 44°C and 52°C at the 100°C, 300°C and 500°C conditions, respectively, and the ETC at each temperature condition was calculated using the temperature gradient obtained from these results.

As a result of comparing the CFD-calculated ETC values with the experimental results of the four TRISO fuel compact specimens measured by Folsom et al., the CFD results were located within the measurement range of the four experimental specimens and showed a result similar to the average variation trend of the experimental values with temperature. Through this, it was confirmed that the STAR-CCM+ CFD analysis results reproducing the experimental conditions of Folsom et al. show reasonable agreement with the experimental data.

These results suggest that the CFD approach based on the MN model can serve as a reliable means of predicting the effective thermal conductivity of TRISO fuel compacts.

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