Sensitivity of Effective Thermal Conductivity Models on Temperature Distribution of Heterogeneous media of Fully Ceramic Micro-encapsulated Fuel

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1. Introduction

One of accident tolerant fuel(ATF) concepts is the Fully Ceramic Micro-encapsulated(FCM) fuel. The FCM fuel pellet concept is based on Tri-isotropic(TRISO) fuel particles embedded in Silicon-Carbide(SiC) matrix. The FCM fuel pellet is designed in a cylindrical form so that it can replace the conventional water reactor fuel pellets. To ensure resistance to hydrogen generation, Zircaloy with SiC or FeCrAl are considered as cladding materials.

A TRISO fuel particle consists of a spherical fuel kernel with four coating layers such as buffer, Inner PyC, SiC, Outer PyC. A FCM fuel pellet contains randomly distributed TRISO particles in a SiC matrix. Such heterogeneous and complicated structure adds difficulty in calculating the realistic temperature distributions in the FCM fuel. General practice is to use a homogenized model using an effective thermal conductivity model.

For these difficulties, a realistic temperature profile on a heterogeneous media is generally calculated on a homogenization model. In this study, we investigate the influence of effective thermal conductivity models on the temperature distribution in a heterogeneous media on FCM fuel pellet.

2. Methods and Results

2.1 Effective conductivity model

For steady state conduction problem, effective thermal conductivity of a composite material is confined within the Wiener bounds. Harmonic-average and arithmetic –average thermal conductivity serves as the lower and upper bounds, respectively. In general effective medium approximation(EMA) predicts a conductivity in Wiener bound. Theoretical effective conducive model by Maxwell[1] has been widely used for heterogeneous media consisting of continuous matrix with dispersed particles.

$$k_c = k_m \frac{\left[2\left(k_d - k_m\right) f + k_m + 2k_m\right]}{\left[\left(k_m - k_d\right) f + k_d + 2k_m\right]} \tag{1}$$

,where k_m is the thermal conductivity of matrix, k_d is that of dispersed particle, f is the volume fraction.

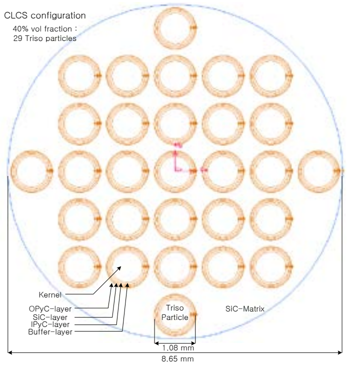
Thermal conductivity of a dispersed TRISO particle can be derived using volume averaged harmonic mean.

$$k_d = \frac{\sum_{i=1}^{5} k_i V_i}{V_{Triso}} \tag{2}$$

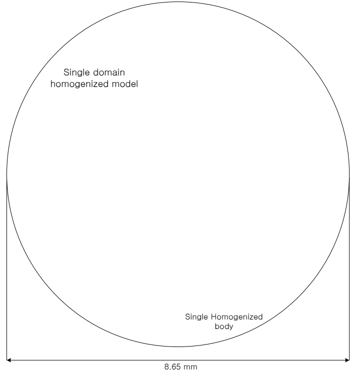
,where k_i is the thermal conductivity of ith layer, V_i is the volume of ith layer, V_{Triso} is the volume of TRISO.

2.2 2-Dimensional model

Temperature distribution in a FCM fuel pellet varies according to the TRISO particles in matrix [2]. Assuming that TRISO particles are not in contact with others in matrix, temperature distribution in matrix is estimated using a Coarse Lattice with Centered Sphere(CLCS) distribution for 40 % of TRISO packing fraction. All layers of TRISO particles were modeled explicitly as shown in Fig. 1-a. Homogenized model consists of one homogenized media of TRISO particles and SiC-matix as shown in Fig. 1-b.



a) 2-D FCM fuel model having 29 TRISO particles with 4 layers



b) Single Domain Homogenization fuel model

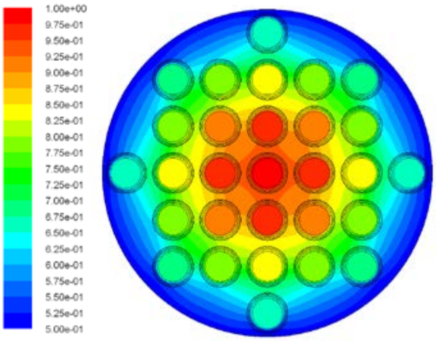
Fig.1. FCM full model and homogenized model

2.3 Results and Discussion

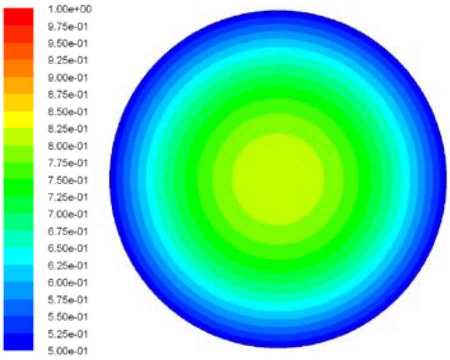
Fuel temperature distribution by the 2-D model is compared with that of the homogenized models having different effective thermal conductivity models as shown in Fig. 1. Calculation conditions are shown in Table. 1.

Table 1. Problem description of a 2-D model

Heat flux	853 kW/m^2
Bulk Temperature	600 K
Heat transfer coefficient	3.1 W/cm^2 K
Materials	Kernel/buffer/IPyC/SiC/OPyC/ SiC-Matrix
Thermal conductivity (W/m K)	23.0/0.2/1.6/14.0/1.6/6.5
Pellet radius(cm)	0.4325



a) Temperature distribution by 2-D model



b) Temperature distribution by SDH with effective conductivity of Maxwell

Fig.2. Temperature distributions of FCM fuel

Fuel temperature distribution by the 2-D model is compared with those of the homogenized models with different thermal conductivities. Four models were explored; 1) effective thermal conductivity by harmonic averaging, 2) effective thermal conductivity by volume averaging, 3) effective thermal conductivity by Maxwell. And 4) optimized effective thermal conductivity model. The effective thermal conductivity was optimized by using the equation below [3].

$$F(k_{\text{homo}}) = \sum_i \left[T_f(r_i) - T_f^{FCM}(r_i) \right]^2 , \qquad (3)$$

Figure 2 shows the 2-D temperature distributions that SDH using Maxwell model predicts well a temperature of matrix and fuel mean temperature within 7% but fuel maximum temperature is under-predicted about 30%.

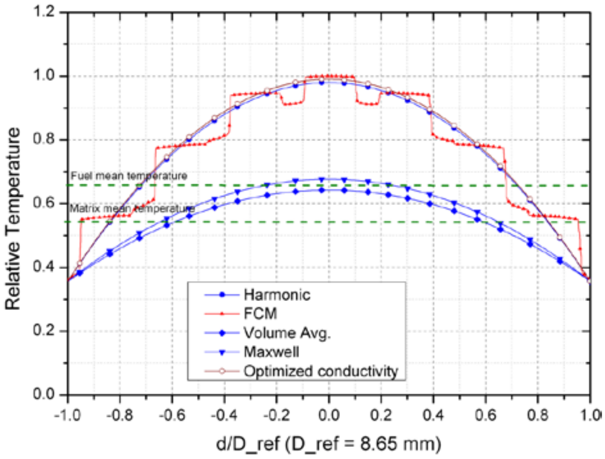


Fig.3. Fuel temperature distribution with effective thermal conductivities

In comparisons of maximum fuel temperatures of FCM 2-D model with other conductivity models, harmonic-averaging, and optimized conductivity model are good agreement within 7% as shown in Fig. 3. Maxwell and volume averaging conductivity models predict well the averaging fuel and matrix temperature.

3. Conclusions

Feasibility of Single Domain Homogenization(SDH) model has been estimated for a heterogeneous media like FCM fuel. From the study, it is found that the effective thermal conductivity is a crucial parameter in analyzing the temperature distributions in SDH approach. Sensitivity of the effective thermal conductivity models indicates that the Maxwell model or an optimized conductivity models are adequate in modeling the heterogeneous FCM fuel.

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