Development of Semi-empirical Thermal Conductivity Model of U-Mo/Al Dispersion Fuel

Tae Won Cho*, Yong Jin Jeong, Kyu Hong Lee, Sung Hwan Kim, Ki Nam Kim, Jong Man Park
Research Reactor Fuel Development Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: twcho@kaeri.re.kr*

1. Introduction

U-Mo/Al dispersion fuel has been developed for a candidate high-performance fuel of high-power research and test reactors worldwide. U-Mo/Al dispersion fuel shows conspicuous microstructure changes during irradiation, which is dependent on the fuel temperature. In this respect, it is important to estimate temperature distribution in the fuel.

In our previous works, the thermal properties of U-Mo/Al dispersion fuel were measured and investigated some microstructure effects [1, 2]. However, it is difficult to apply the measured data to fuel performance analysis since it is applicable only to limited fuel conditions. Therefore, it is necessary to develop a semi-empirical model, which is conveniently applicable to various fuel conditions.

Fig. 1 shows a typical microstructure of U-Mo/Al dispersion fuel and an illustration for a typical heat transfer in a particle-dispersed system. Heat can be transferred through the particles or the matrix. The heat paths can be simplified and distinguished as follows:

1. Only through medium
2. Particle contact conduction
3. Both particles and matrix sequentially

In this work, a semi-empirical model was developed to consider various fuel conditions.

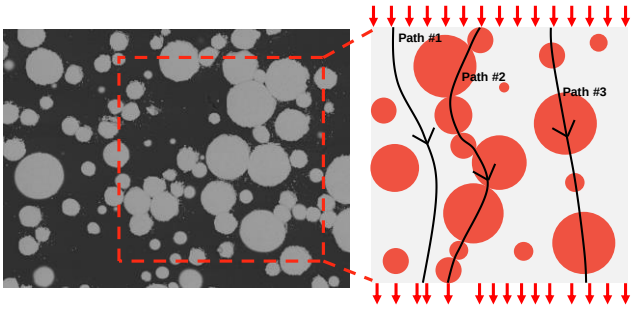


Fig. 1. Schematic representation of heat-transfer pathways in a particle dispersed system.

2. Developments of Semi-empirical Model

2.1 Modeling of unit-cell

First, we supposed a unit-cell composed of a particle embedded in a matrix as seen in Fig. 2. Solving the temperature distribution functions and boundary conditions in Fig. 2, Phelan [3] attained the effective thermal conductivity of unit-cell as below:

$$k_{unit} = k_m \left(1 - \frac{\psi}{\sqrt{\psi+1}}\right) \tan^{-1}\left(\frac{1}{\sqrt{\psi+1}}\right)$$

where

$$\psi = \frac{\left(\frac{k_m}{k_p}\right) + \left(\frac{k_m}{dh_c}\right) - 1}{\left(\frac{k_m}{k_p}\right) + \left(\frac{k_m}{dh_c}\right) + 1}$$

where k_m and k_p indicate the thermal conductivities of matrix and particle, h_c is the interfacial thermal resistance, and d is the length of the unit-cell.

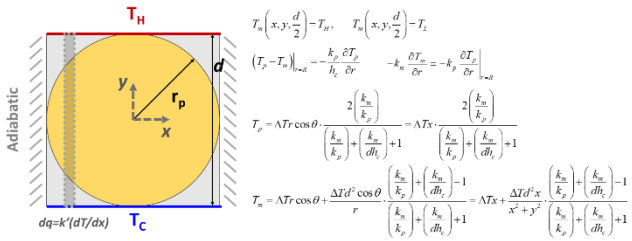


Fig. 2. Schematic of the unit-cell and temperature distribution functions in particle and matrix.

2.2 Modeling of contact conductance

Since heat can be transferred through the contact conductance between particles, we adopted a classical contact mechanics theory. According to the Hertz contact theory [4], the particle contact conductance can be expressed as:

$$\mathrm{k_c} = \beta \frac{2k_p a_L}{\left(1 - \frac{a_L}{r_p}\right)^{1.5}}$$

where a_L is the contact radius ($a_L = \sqrt[3]{3r_p F/4E_p}$), β is an accommodation factor which is used to make up for the omitted micro-contact thermal resistance, k_p is the particle thermal conductivity, and r_p is the particle radius.

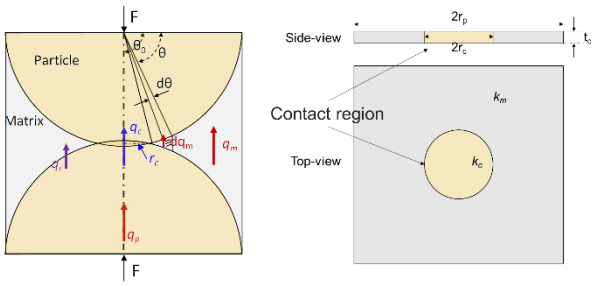


Fig. 3. Schematics of particle contact conductance.

The contact conductance increases as the particle contact increases. In general, the particle contact increases as the particle packing fraction increases or the particle size decreases. Since the U-Mo particles have a random particle distribution, the effect of particle size was assumed to be negligible. To estimate the ratio of contact, a contiguity ratio was measured in ANL and an empirical equation was suggested as follows [5]:

$$C_r = 0.054 - 0.2779 \times v_c + 0.8083 \times v_c^2$$

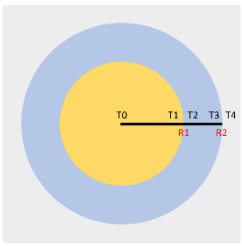
where v_c is the total volume fraction of fuel and interaction layer (IL) phases.

2.3 Modeling of a composite particle

The thermal conductivity of IL-formed particle was derived by solving the heat transfer equation for a layer-structured particle as seen in Fig. 4. The temperature conditions at the boundaries were given as in Fig. 4. Combining the temperature conditions, the effective thermal conductivity of the layer-structured particle, k_{cp} can be obtained so that:

$$k_{cp} = \frac{1}{\frac{r_p + t_l}{r_p^2}\left(\frac{r_p}{k_{UMo}} + R_1\right) + \frac{1}{r_p + t_l}\left(\frac{t_l}{k_{IL}} + R_2\right)}$$

where r_p and t_l denote is the radius of particle and layer thickness, R_1 and R_2 are the interfacial thermal resistances between U-Mo-IL, and IL-Al, respectively.



For composite particle

$$T_0 - T_1 = \frac{Q(r+t)}{4\pi(r+t)^2 k}$$

For separate layers

$$T_0 - T_1 = \frac{Qr}{4\pi r^2 k_{UMo}} \qquad T_2 - T_3 = \frac{Qt}{4\pi(r+t)^2 k_{IL}}$$

$$T_1 - T_2 = \frac{QR_1}{4\pi r^2} \qquad T_3 - T_4 = \frac{QR_2}{4\pi(r+t)^2}$$

Fig. 4. An illustration of layer-structured particle and its temperature at the boundaries.

2.4 Homogenization

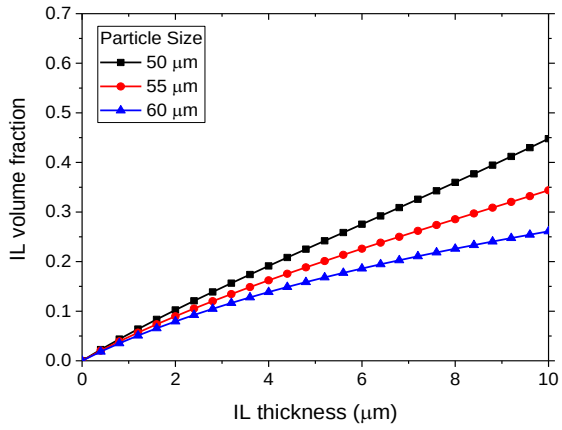
For a randomly distributed system, heat transfer paths are mixed randomly. Therefore, the effective thermal conductivity can be expressed in non-dimensionless form using a geometric mean equation as follows [6]

$$\left(k_{eff}^*\right)^\alpha = 1 + \sum_{\text{mode}=1}^{n} v_i\left(k_i^\alpha - 1\right)$$

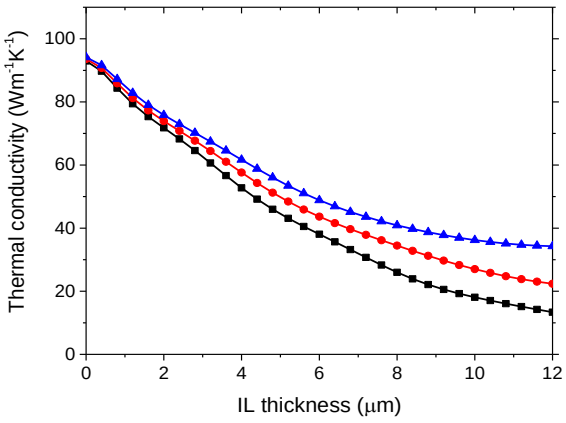
where α is the empirical constant indicating the mixed ratio of parallel and series mode. Note that when α =1: parallel model; α =-1: series model. Therefore, the α indicates a heterogeneity factor for the system mixing. As the α is close to 1, it means the heat transfer modes are mostly mixed parallel while the system has a more serially mixed composition as the α is close to -1. In this respect, α is dependent on the microstructures of a fuel such as particle packing fraction, particle size distribution, and material properties. Therefore, the α should be obtained as an empirical constant from the measured data.

2.5 Prediction of thermal conductivity of U-Mo/Al dispersion fuel

Using the semi-empirical model, thermal conductivity of IL-formed U-Mo/Al dispersion fuel was estimated. The analyses were performed for the cases when U-Mo volume fraction is 0.50. Three average particle sizes of 50, 55, and 60 μm were considered to investigate and verify the effects of particle size. Fig. 5 shows the IL volume fraction and thermal conductivity variations with IL thickness. As the particle size is smaller, the IL growth is faster, and the thermal conductivity decreases more rapidly. This overall trend is consistent with the measured data. Therefore, it seems that the semi-empirical model successfully predicts the thermal conductivity of U-Mo/Al dispersion fuel considering the IL growth as well as the particle size effect.



(a) IL volume fraction



(b) Effective thermal conductivity

Fig. 5. Model prediction for IL volume fraction and its thermal conductivity as a function of IL thickness

3. Conclusions

The thermal conductivity of U-Mo/Al dispersion fuel is dependent on the microstructure characteristics such as uranium loadings, materials, IL thickness, and particle size and distribution. In this work, we developed a semi-empirical model, which can consider the microstructure effects. The semi-empirical model was developed based on the unit-cell model. Three heat transfer mechanisms were assumed: fully through matrix, particle-matrix conduction, and particle contact conduction. The model prediction showed consistent results as a function of U-Mo volume fraction and IL thickness, which successfully proved a good reproducibility and reliability. In addition, the model considered particle size effects. In the future, the model will be applied to a fuel performance code and its applicability will be proved.

REFERENCES

[1] T.W. Cho, Y.S. Kim, J.M. Park, K.H. Lee, S.H. Kim, C.T. Lee, J.H. Yang, J.S. Oh, J.J. Won, D.S. Sohn, Thermal properties of U-7Mo/Al dispersion fuel, J. Nucl. Mater., 496, (2017), 274.
[2] T.W. Cho, Y.S. Kim, J.M. Park, K.H. Lee, S.H. Kim, C.T. Lee, J.H. Yang, J.S. Oh, D.S. Sohn, Thermophysical properties of heat treated U-7Mo/Al fuel, J. Nucl. Mater., 501, (2018), 31.
[3] P.E. Phelan, R. Prasher, An Effective Unit Cell Approach to Compute the Thermal Conductivity of Composites with Cylindrical Particles, J. Heat Transfer, 127, (2005), 554.
[4] X. Zhu, Tutorial on Hertz Contact Stress, In: Opti., 521, (2012), 1.
[5] ANL unpublished data
[6] J. Mo, H. Ban, Measurements and theoretical modeling of effective thermal conductivity of particle beds under compression in air and vacuum, Case Studies in Thermal Engineering, 10, (2017), 423.