Thermal Conductivity Analysis of U-Mo/Al Dispersion Fuel Using FEM Simulation

Tae Won Cho [a,*], Dong-Seong Sohn [b], Yong Jin Jeong [a], Kyu Hong Lee [a], Sung Hwan Kim [a], Ki Nam Kim [a], Jong Man Park [a],
a: Research Reactor Fuel Development Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
b: Nuclear Engineering Department, Ulsan National Institute of Science and Technology, 44919, unist-gil 50, Ulju-gun, Ulsan, Republic of Korea
[*]Corresponding author: twcho@kaeri.re.kr

1. Introduction

In the last few decades, U-Mo/Al dispersion fuel has been developed for a next fuel of research or test reactor to convert highly enriched uranium (HEU) fuel with low enriched uranium (LEU) fuel due to its high uranium density and acceptable irradiation performances [1]. The most favorable design of U-Mo/Al dispersion is a plate type as seen in Fig. 1. The fuel meat composed of U-Mo fuel and Al matrix was clad with Al alloy.

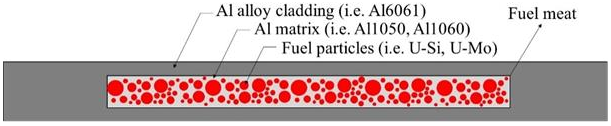
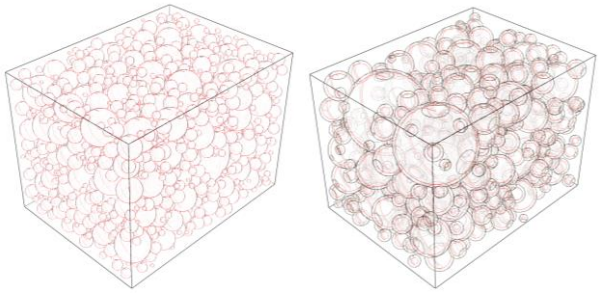


Fig. 1. A cross-sectioned schematic of a typical dispersion type of plate

In U-Mo/Al dispersion fuel, thermal conductivity is critical on its irradiation behaviors. For example, the operational temperature controls the growth kinetics of IL between U-Mo particles and Al matrix. However, the thermal conductivity of U-Mo/Al dispersion fuel has not been clearly understood since it is dependent on the various microstructure parameters such as volume fraction of phases, heterogeneity, size and isotropy of dispersants. In our previous studies [2], [3], the thermal conductivity of U-Mo/Al dispersion fuel was measured systemically. However, it is difficult to understand the microstructure effects only from the measured data. In this study, parametric studies were performed using finite element method (FEM) simulation to investigate the effects of various parameters inherent in the U-Mo/Al dispersion fuel

2. Analysis Methods

Heat transfer simulation was performed using a FEM software, ABAQUS CEA. A hypothetical U-Mo/Al dispersion system was designed to analyze the effects of various parameters inherent in the U-Mo/Al dispersion fuel. A Python module was developed and adopted to generate random particle distribution database. Abaqus PDE was utilized to generate a heat transfer model. The model enables various parametric studies by allowing various particle size distribution, uranium loadings, materials, and layer thickness. For the case of fresh fuel, particle packing fractions were set to be 10, 20, 30, 40, and 50 vol.%. For the case of layer formed fuel, particle packing fractions were set to be 30, 40, and 50 vol.% with various layer thicknesses. Boundary conditions and calculation of effective thermal conductivity are described in ref. [4]

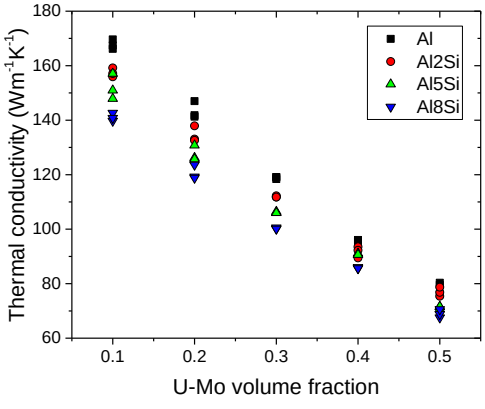


(a) (b)

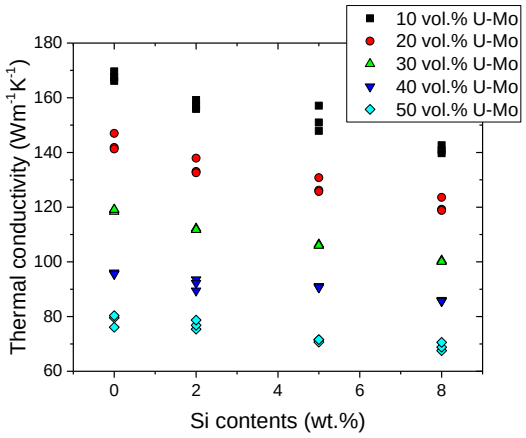
Fig. 2. An example of three-dimensional FEM model: (a) particle packing fraction of 0.50 without IL; (b) particle packing fraction of 0.40 with 5 μm layer.

3. Results and Discussion

Fig. 3 shows the thermal conductivity of U-Mo/Al-Si in terms of U-Mo volume fraction and Si content. The simulation results showed a linear decrease with U-Mo volume fraction regardless of Si amounts in Al matrix. However, the reduction ratio gets smaller as the Si content increases.



(a)



(b)

Fig. 3. FEM simulation results for thermal conductivity of U-Mo/Al-Si as a function of U-Mo and Si contents.

Since the fabrication of IL is impossible, the thermal conductivity of IL has been left unknown. Alternatively, the thermal conductivity of IL can be estimated from the thermal conductivity of IL-formed U-Mo/Al dispersion fuel. In this study, a uniform thickness of IL was considered and the particle packing fraction was set to be constant in order to ignore the effects of U-Mo volume fraction. The thermal conductivity of IL was assumed to be 1, 3, 6, and 10 W/m/K.

The simulation results were compared with measured data. The empirical prediction was obtained from the measured data [2], [3]. Although the valid IL volume fraction in the empirical prediction is very narrow and the effects of IL thermal conductivity are observed less strongly, it gives the best estimated IL thermal conductivity to be approximately 5 $Wm^{-1}K^{-1}$. The simulation results were obtained for more expanded IL volume fraction. It decreases linearly at lower IL ranges, but it converges exponentially to a certain value. The value is dependent on the IL thickness.

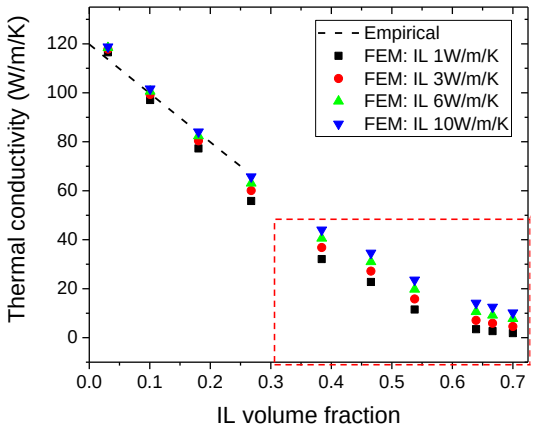


Fig. 4. Comparison of thermal conductivity of 5.0 gU/cm^3 U-7Mo/Al dispersion fuels with a function of IL volume fraction between the measured and the simulated results.

The thermal conductivity of U-Mo/Al dispersion fuel is largely affected by the formation of pores formed during irradiation as well. Two types of pores were formed: very tiny pores within U-Mo particles and relatively large pores between IL and Al. Up to date, the Cunningham model [5] has been adopted arbitrarily. Since the pores are formed at the boundary between IL and Al, it can be considered that pores exist in the Al matrix. Hence, the porosity effect was evaluated by simulating Al matrix with various porosity. According to some PIE results, it was reported that the biggest pore size is smaller than 20 μm. Accordingly, it was assumed that the pore size ranges from 0 – 20 μm. Since the maximum porosity should be lower than the 20 %, the porosity was assumed to be 1, 3, 5, 10, 15, and 20 %. Fig. 5 shows a comparison of relative thermal conductivity between theoretical models and FEM results as a function of porosity. The FEM results were most consistent with the Maxwell-Eucken model [6], while the Cunningham model [5] gave a quite lower estimation.

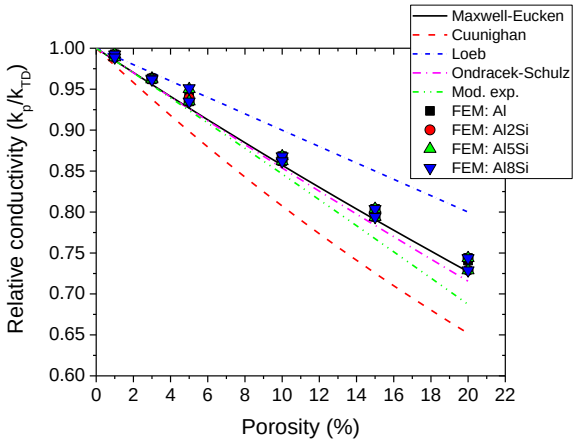


Fig. 5. A comparison of relative thermal conductivity between theoretical models and FEM results as a function of porosity.

Coating U-Mo particles with a ternary phase has been considered to retard inter-diffusion between U-Mo and Al. There are many candidates coating materials such as ZrN, Si, Mo, UN, and UO_2. The thermal conductivity of coated U-Mo/Al dispersion fuel is dependent on the thermal conductivity of coating material and the coating thickness. However, the effects of coating on the thermal conductivity of U-Mo/Al dispersion fuel has not been systemically analyzed.

In this work, the thickness of coating layer was assumed to be 1 μm and the thermal conductivity of coating material was assumed to be 1, 3, 5, 10, 20, 30, 40, 50, 60, 75, and 100 W·m−1·K−1, respectively. The U-Mo volume fractions were considered to be 0.30, 0.40, and 0.50. Fig. 6 shows the effects of thermal conductivity of coating material. It showed a linear increase in the case of thermal conductivity of coating material higher than that of U-Mo while an exponential

decrease when the thermal conductivity of coating material is lower that that of U-Mo. However, the effects of the coating itself were not remarkable.

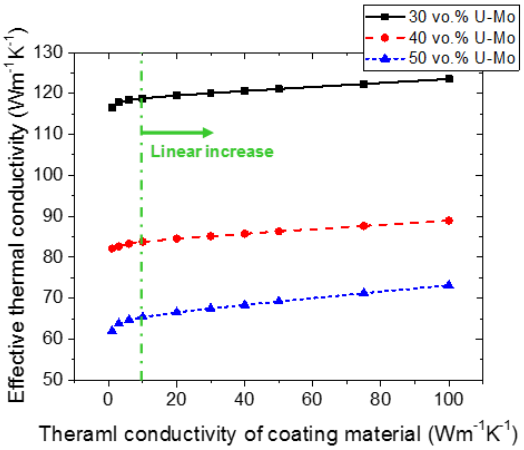


Fig. 6. Effects of thermal conductivity of coating material.

3. Conclusions

Thermal conductivity of U-Mo/Al dispersion fuel was analyzed using FEM simulation. It gave compatible data with measured data indicating the feasibility of FEM application. FEM simulation enables various parametric studies about uranium loadings, Si contents in Al matrix, porosity, and coating effect. It seems that all the results were reasonable and they can be utilized for thermal conductivity modeling. In addition, the thermal conductivity of IL was evaluated, which is approximately 5 $Wm^{-1}K^{-1}$.

Acknowledgement

This work was supported by the Nuclear R&D program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2017M2A8A1066681).

REFERENCES

[1] Y.S. Kim, Uranium Intermetallic Fuels (U-Al, U-Si, U-Mo), In: R.J.M. Konings (ed.), Comprehensive Nuclear Materials, 3, Elsevier, (2012), 391.
[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, J.J. Won, D.S. Sohn, Thermal properties of U-7Mo/Al dispersion fuel, J. Nucl. Mater., 496, (2017), 274.
[3] 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.
[4] T.W. Cho, D.S. Sohn, Y.S. Kim, Thermal conductivity of U-Mo/Al dispersion fuel: effects of particle shape and size, stereography, and heat generation, J. Nucl. Sci. Technol., 52, (2015), 1328.
[5] M.E. Cunningham, K.L. Peddicord, Heat Conduction in Spheres Packed in an Infinite Regular Cubic Array, Int. J. Heat Mass Transfer, 24, (1981), 1081
[6] J. C. Maxwell, A treatise on electricity and magnetism: Clarendon press, 1, (1881).