Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Thermal conductivity of U-Mo/Al dispersion fuel

Tae Won Cho [a], Yeon Soo Kim [b], Jong Man Park [c], Kyu Hong Lee [c], Sunghwan Kim [c], Chong-Tak Lee [c], Jae Ho Yang [c], Jang Soo Oh [c], Dong-Seong Sohn [a*]
[a] *Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Eonyang-eup, Ulju-gun, Ulsan 689-798, Republic of Korea*
[b] *Argonne National Laboratory, 9700 S. Cass Ave, Argonne, IL 60439, USA*
[c] *Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong-gu, Daejeon 305-353, Republic of Korea*
[*]Corresponding author: dssohn@unist.ac.kr

1. Introduction

U-Mo/Al dispersion fuel has been developed for a next research or test reactor fuel to convert high-enriched uranium (HEU) with low-enriched uranium (LEU). The typical fuel design is a plate where a fuel meat is enclosed with Al cladding. The fuel meat is a mixture zone where spherical U-Mo particles are dispersed in an Al matrix [1], [2].

One of the major microstructure changes is a formation of interaction layer (IL) between U-Mo and Al, which degrades the fuel integrity. The formation of IL and consumption of Al matrix lead a severe decrease in thermal conductivity. Consequently, the centerline temperature in the fuel meat increases, which accelerates the formation of IL in the way of positive feedback [3]-[5]. Many post-irradiation examinations (PIEs) proved that adding Si to the Al matrix (using Al-Si alloy) is effective in suppressing the IL growth [6].

In general, the thermal conductivity of U-Mo/Al dispersion fuel is governed by the volume fractions of fuel meat constituents such as U-Mo, Al(-Si), and IL. However, there are very limited measured data for the thermal conductivity of U-Mo/Al dispersion fuel. Especially, the thermo-physical information of IL is still unknown. In this work, the thermal conductivities of fresh U-Mo/Al(-Si) and heat-treated U-Mo/Al fuel samples were measured with various U-Mo and IL volume fractions.

2. Experimental

2.1 Sample preparation

The fresh U-Mo/Al samples were fabricated by hot-extrusion at 400 °C in Ar condition. The extrusion was repeated three to five times to obtain improved particle homogeneity, low porosity, and negligible IL growth. Both U-7Mo/Al and U-7Mo/Al-5Si fuels were prepared with different uranium loadings of 5.0, 6.5, and 8.0 gU/cm^3. The fresh fuels were heat-treated in various conditions to produce a desirable amount of IL. The heating temperatures were in the range of 475 – 530 °C.

2.2 Sample characterization

To obtain a sample integrity, the microstructures of samples were examined using scanning electron microscope (SEM). Fig. 1 shows microstructure images of fresh and heat-treated samples. There were no visible pores and ILs in the fresh fuel. Uniform IL was formed around U-Mo particles in heat-treated samples, which still has no remarkable pores.

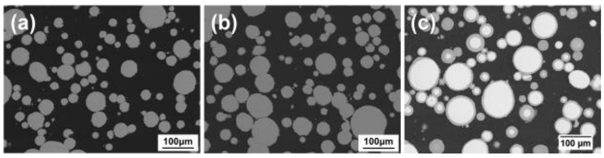


Fig. 1. Microstructure images of 5.0 gU/cm^3 samples: (a) as-fabricated U-7Mo/Al, (b) as-fabricated U-7Mo/Al-5Si, (c) heat-treated U-7Mo/Al.

The composition of IL was analyzed using an X-ray energy dispersive spectrometry (EDS) method. Fig. 2 shows an example of EDS line scan. The ratio of Al/(U+Mo) in the IL is mainly distributed in a range of 3 – 4. The average values were obtained to be 3.7.

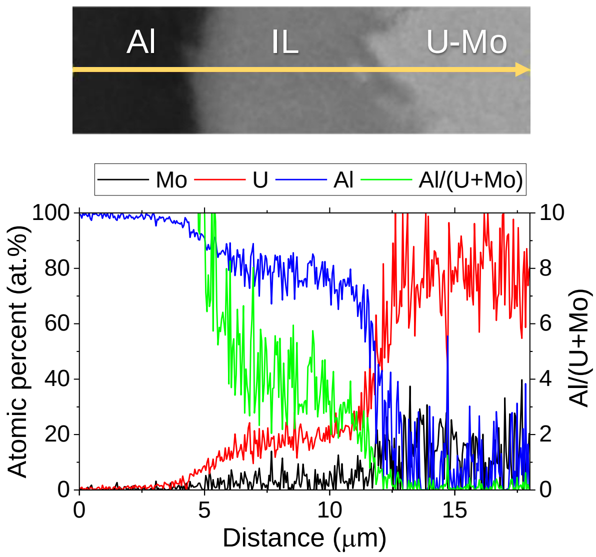


Fig. 2. EDS line scan along Al-IL-U-Mo in a heat-treated U-Mo/Al sample [7].

2.3 Measurements of thermo-physical properties

Density of samples was measured using Archimedes' method. The uranium density of samples was estimated from the measured density. For heat-treated samples, the density was measured both before and after heat-treatments. The volume fraction (or area fraction) of IL was measured using image analysis.

Thermal diffusivity of samples was measured using laser flash method in the temperature range of 25 – 400 °C. The pulses were corrected using the Cowan model.

Heat capacity of samples was measured using differential scanning calorimetry (DSC). The heat flow was measured in the temperature range of 25 – 400 °C with an interval of 50 °C, thus total of eight heating cycles for each measurement. The heating rate was set to 5 °C/min.

3. Results

Using the thermal diffusivity, heat capacity, and density, thermal conductivity of U-Mo/Al dispersion fuel can be calculated as follows:

$$k = \alpha \cdot C_p \cdot \rho \qquad (1)$$

where k is the thermal conductivity, α is the thermal diffusivity, C_p is the heat capacity, and ρ is the density.

3.1 Thermal conductivity of fresh fuel

The thermal conductivity of fresh U-7Mo/Al and U-7Mo/Al-5Si is obtained as a function of temperature and U-Mo volume fraction. As shown in Fig. 3, the thermal conductivity of U-7Mo/Al decreases with temperature at low U-Mo volume fractions. This trend, however, gradually diminishes as the U-Mo volume fraction increases and the thermal conductivity increases with temperature for the higher uranium loadings. For U-7Mo/Al-5Si, the thermal conductivity increases with temperature for all U-Mo volume fraction. This is because the thermal conductivity of Al-5Si decreases weakly with temperature. Thus the thermal conductivity of the sample is dominated by the increase in the thermal conductivity of U-Mo with temperature. Fig. 4 shows the thermal conductivities of U-7Mo/Al and U-7Mo/Al-5Si as a function of U-Mo volume fraction. The thermal conductivity decreases monotonically with U-Mo volume fraction [7].

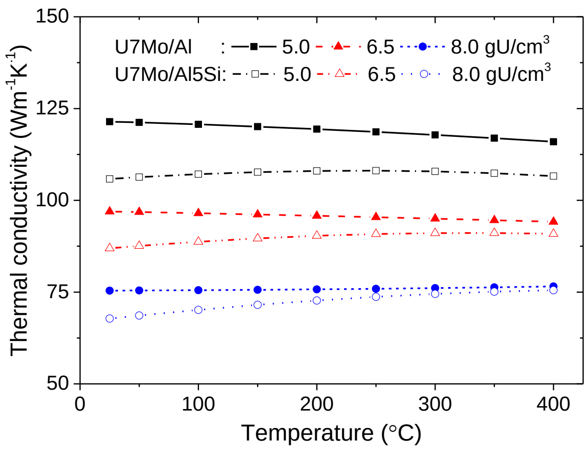


Fig. 3. Thermal conductivity of U-7Mo/Al and U-7Mo/Al-5Si with different uranium densities as a function of temperature [7].

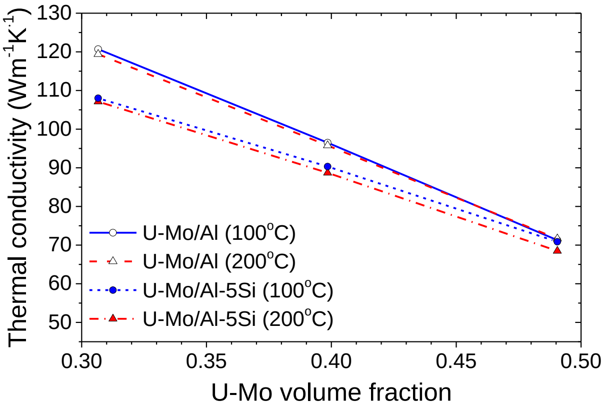
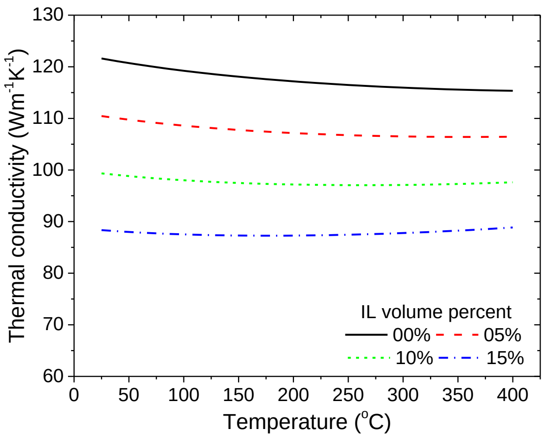


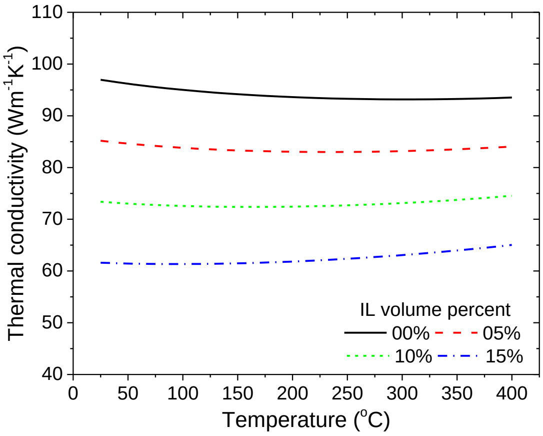
Fig. 4. Thermal conductivity of U-7Mo/Al and U-7Mo/Al-5Si as a function of U-Mo volume fraction [7].

3.2 Thermal conductivity of IL-formed fuel

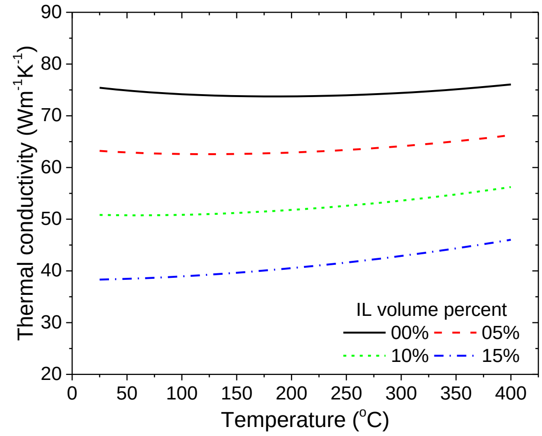
From the measured data of heat-treated samples, the thermal conductivity of U-7Mo/Al is obtained as a function of temperature with different U-Mo and IL volume fractions as shown in Fig. 5. Likewise with fresh fuel, the thermal conductivity decreases with temperature when the volume fraction of U-Mo and IL is low but gradually change to increase as the volume fraction increases [8].



(a) 5.0 gU/cm^3



(b) 6.5 gU/cm^3



(c) 8.0 gU/cm^3

Fig. 5. Thermal conductivity of U-7Mo/Al with different IL volume percent as a function of temperature [8].

Fig. 6 shows the thermal conductivity changes as a function of IL volume fraction. Regardless of uranium density and temperature, the thermal conductivity decreases monotonically with IL volume fraction. The slope gets weak as the temperature increases. However,

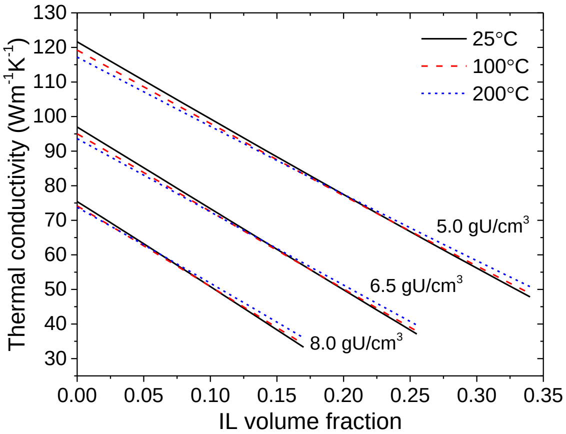


Fig. 6. Thermal conductivity of U-7Mo/Al as a function of IL volume fraction [8].

the temperature effects are not significant compared to U-Mo and IL effects.

3.3 Uncertainty analysis

The uncertainty for the laser flash measurement is mainly due to the finite pulse time effect, non-uniform heating, and heat losses from the sample. The laser pulse was corrected with the Cowan model and the uncertainty was automatically calculated in the software. The uncertainties are approximately in the range 2 – 5 % for each measurement. For the heat capacity, uncertainty is mainly caused by the heat flow and mass deviation. The uncertainty in the data is also 2 – 5 %.

3. Conclusions

Thermal conductivity of U-Mo/Al dispersion fuel was systemically measured as a function of temperature and volume fraction of U-Mo and IL.

- As the volume fractions of U-Mo and IL increase, the thermal conductivity decreases linearly.
- As the volume fraction of Al decreases, thermal conductivity tends to increase with temperature.
- The thermal conductivity decreases when Si is added to Al matrix. The gap between U-7Mo/Al and U-7Mo/Al-5Si decreases as the uranium loadings increase.

Acknowledgments

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 (NRF-2016M2A8A1930062).

REFERENCES

[1] Y.S. Kim, Uranium Intermetallic Fuels (U-Al, U-Si, U-Mo), In: R.J.M. Konings (ed.), Comprehensive Nuclear Materials, Vol.3, p.391, Elsevier, 2012

[2] S. Van den Berghe, P. Lemoine, Review of 15 years of high-density low-enriched UMo dispersion fuel development for research reactors in Europe, Nucl. Engin. Technol., Vol. 46, p. 125, 2014

[3] H.J. Ryu, Y.S. Han, J.M. Park, S.D. Park, C.K. Kim, Reaction Layer Growth and Reaction Heat of U–Mo/Al Dispersion Fuels Using Centrifugally Atomized Powders, J. Nucl. Maters., Vol.321, p.210, 2003

[4] H.J. Ryu, J.M. Park, C.K. Kim, Y.S. Kim, G.L. Hofman, Diffusion Reaction Behaviors of U-Mo/Al Dispersion Fuel, J. Phase Equilibria and Diffusion, Vol.27 p.651, 2006

[5] H.J. Ryu, Y.S. Kim, J.M. Park, H.T. Chae, and C.K. Kim, Performance Evaluation of U-Mo/Al Dispersion Fuel by Considering a Fuel-Matrix Interaction, Nucl. Engin. Technol., Vol.40, p.409, 2008

[6] Y.S. Kim, J.M. Park, H.J. Ryu, Y.H. Jung, G.L. Hofman, Reduced interaction layer growth of U-Mo dispersion in Al-Si, J. Nucl. Mater. Vol. 430, p.50, 2012

[7] T.W. Cho, Y.S. Kim, D.-S. Sohn, et al., Thermal properties of U-7Mo/Al dispersion fuel, J. Nucl. Mater., (submitted), 2017

[8] T.W. Cho, Y.S. Kim, D.-S. Sohn, et al., Thermo-physical properties of heat-treated U-7Mo/Al dispersion fuel, J. Nucl. Mater., (submitted), 2017