A Recommendation for the Thermal Conductivity of Oxide Fuels

K.H. Kang, H.J.Ryu, K.C. Song, M.S. Yang, S.H. Na, Y.W. Lee, H.S. Moon, H.S. Kim
Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, Daejeon, Korea, 305-600
nghkang@kaeri.re.kr

1. Introduction

The thermal conductivity of nuclear fuel is one of the most important properties because it affects the fuel operating temperature. Therefore, it influences almost all the important processes occurred in nuclear fuel during irradiation, such as gas release, swelling and grain growth.

The model of the thermal conductivity of nuclear fuel should be used in the codes to evaluate the performance of it analytically and be required in the nuclear fuel research and development. The thermal conductivity, k, of UO_2 depends on the deviation from stoichiometry, x, the burnup, b, and the fractional porosity, p, as well as the temperature, T:

$$k = k(x, b, p, T), \qquad (1)$$

Changes in thermal conductivity occur during irradiation because of fission-gas bubble formation, pores, cracks, fission product build-up and possible changes in the oxygen to uranium ratio (O/U). The dependence on temperature and porosity has been well studied and incorporated in computer codes used for the in-pile fuel behavior analysis. There are several studies on the effect of impurity on the thermal conductivity of UO_2.

In this paper, the variables affected on the thermal conductivity were studied. The available data of the thermal conductivity of UO_2, UO_{2+x}, (U, Pu)O_2, (U, Pu)O_2 and simulated fuel for irradiation fuel were reviewed and analyzed. The best models were recommended.

2. The thermal conductivity model of oxide fuel

The conduction heat transfer means movement of the thermal energy from high temperature region to low temperature region to make thermal equilibrium through the substance. The thermal conductivity is the intrinsic property to characterize the heat transfer capacity of material. It is generally accepted that heat is mainly conducted in UO_2 by phonons and small polarons, these two mechanisms being comparatively more important at low and high temperatures, respectively.

$$k = k_{ph} + k_{po} \qquad (2)$$

where k is thermal conductivity (W m^{-1} K^{-1}) and k_{ph} and k_{po} represent the thermal conductivity component due to the phonon and polaron, respectively.

It is well known that the thermal conductivity of UO_2 decreases with temperature up to 1900 K. At the low temperatures, the phonon contribution is predominant and as the temperature increases, the magnitude of the phonon component goes down due to a decrease in the mean free path of phonons between scattering events. While at high temperatures heat is conducted predominantly by small polarons, the contribution of phonon is negligible. Above 1900 K, the thermal conductivity of UO_2 increases with temperature.

The thermal conductivity model may be written as the hyperbolic term represented the phonon contribution and the exponential term represented the small polaron contribution

$$k = \frac{1}{C_1 + C_2 t + C_3 t^2} + \frac{C_4}{t^{5/2}} \exp\left(-\frac{C_5}{T}\right), W/m \bullet k \qquad (3)$$

where k is the thermal conductivity, $t = T/1000, T$ is temperature C_1, C_2, C_3, C_4 and C_5 are constants

3. Recommendation for the Thermal Conductivity

3.1 UO_2

Model for the thermal conductivity of UO_2 proposed by Fink and Petri [1] is recommended in this study.

$$k = \frac{1}{7.54 + 17.7t + 3.61t^2} + \frac{7411.2}{t^{5/2}} \exp\left(-\frac{16.35}{T}\right), W/m \bullet k \qquad (4)$$

Figure 1 represents the thermal conductivity UO_2 recommended in this study with the various results for the purpose of comparison. There are some difference between the other results and our recommendation below 500 K and over 2000 K.

3.2 UO_{2+x}

Model for the thermal conductivity of UO_{2+x} proposed by Popov et al. [2] is recommended in this study. He proposed the model combined the Ronchi's model [3] representing the Polaron contribution and Duriez's model [4] representing the phonon contribution on the thermal conductivity of UO_{2+x}.

$$k = \frac{1}{(0.03 + 3.34\,x) + (0.22 - 0.69\,x)\,t} + \frac{7411.2}{t^{5/2}} \exp\left(-\frac{16.35}{T}\right), W/m \bullet k \quad (5)$$

Figure 2 represents the thermal conductivity of UO_{2+x} recommended in this study with deviation from stoichiometry. As the x increases, it decreases and the effect of deviation from stoichiometry on it in the low temperature region is large and decreases as the temperature increases.

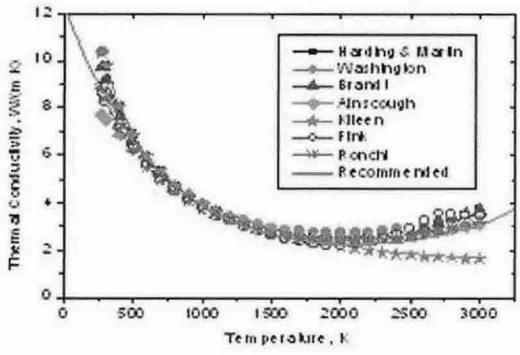

Fig. 1. Thermal conductivity of UO_2

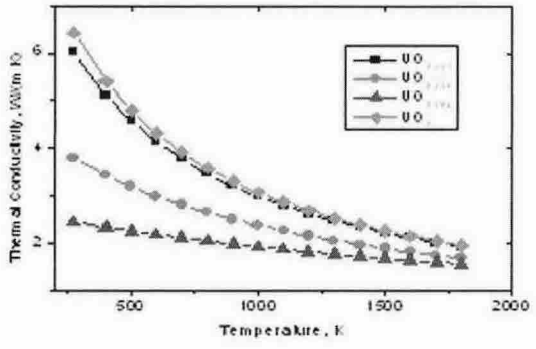

Fig. 2. Thermal conductivity of UO_{2+x}

3.3 MOX (3-15% Pu)

The thermal conductivity of MOX (3-15% Pu) is higher than that of UO_2 and the effect of Pu content on the thermal conductivity is negligible. Model for the thermal conductivity of MOX proposed by Popov et al. [2] is recommended in this study.

$$k = \frac{1.1579}{(0.035 + 2.85\,x) + (0.286 - 0.715\,x)\,t} + \frac{7411.2}{t^{5/2}} \exp\left(-\frac{16.35}{T}\right), W/m \bullet k \quad (6)$$

3.3 Simulated fuel for irradiated fuel

Model for the thermal conductivity of simulated fuel below the temperature of 1773 K proposed by Lucuta et al. [5] is recommended in this study.

- 3 at% burnup

$$k = \frac{1}{0.136 + 0.212\,t} \quad (7)$$

- 8 at% burnup

$$k = \frac{1}{0.186 + 0.205\,t} \quad (8)$$

4. Conclusion

In this paper, the variables affected on the thermal conductivity were studied. The available data of the thermal conductivity of UO_2, UO_{2+x}, (U, Pu)O_2, (U, Pu)O_2 and simulated fuel for irradiation fuel were reviewed and analyzed. The best models were recommended. The recommended models for the thermal conductivity of oxide fuel may be useful for developing a fuel performance estimation codes.

REFERENCES

[1] J.K. Fink and M.C. Petri, ANL, RE-97/2, February (1997)
[2] S. G. Popov, J. J. Carbajo, V. K. Ivanov and G. L Yodar ORNL/TM-2000/351(2000)
[3] C. Ronchi and M. Sheindin and M. Musella J. Applied Physics 15(1999)776
[4] C. Duriez, J. Allessandri, T. Gervais, Y. Philipponneau, J. Nucl. Mater. 277 (2000) 143
[5] P. G. Lucuta, Hj. Matzke and I. J. Hastings J. Nucl. Mater. 232(1996)166
[6] J. H. Harding and D. G. Martin J. Nucl. Mater. 166(1989)223
[7] A.B.G. Washington, TRG report 2236(D), 1973
[8] R. Brant and G. Neuer, J. Non-quilib. Thermodyn. 1, (1976) 3
[9] J.B. Ainscough, Springfields Nuclear Power Development Lab., (1972) as referenced by Martin in J. Nucl. Mater. 110(1982)73
[10] G. Killeen, Berkeley Nuclear LaB. (1980) as referenced by Martin in J. Nucl. Mater. 110(1982)73