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Modeling of Effective Thermal Conductivity for the ATF Pellets of Micro-cell UO_2

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1. Introduction

Metallic micro-cell UO_2 pellets, in which UO_2 granules are surrounded by a wall of metal, are being developed in KAERI as a part of the Accident Tolerant Fuel development program. The key benefit of this pellet is an enhanced thermal conductivity. It was shown that formation of cell wall in the UO_2 matrix with 5 vol% of metal additives leads to an increase in thermal conductivity between 70% and 100%, as compared to the UO_2, in the temperature range 200-1200°C [1].

Thermal conductivity of a fuel is one of the most important thermo-physical properties governing the fuel performance and safety. The modeling of effective thermal conductivity is therefore essential to evaluate performance and safety benefits.

In this study, we are suggesting the effective thermal conductivity equation for non-irradiated fresh microcell UO_2 pellets as a function of temperature and wall volume. We have explored analytic models of effective thermal conductivity those best predict measurement results. Thermal conductivity curves in expanded temperature range were plotted using selected analytical model. Finally, we have converted the curves into a typical form of thermal conductivity equation in the FRAPCON code [2]. The effect of burn-up on the effective thermal conductivity of micro-cell UO_2 pellets is also estimated.

Since the current thermal conductivity modeling is based on the limited measurement data for non-irradiated samples, the model equation in this study is preliminary one. The parameters in the model will be modified further as measurement data accumulates.

2. Analytical Model

2.1 Anisotropy of thermal conductivity

Fig. 1 shows the thermal conductivity curves measured for 5vol% of Mo containing microcell UO_2 pellet. The curves for microcell pellet show a large increase in thermal conductivity compared to UO_2 and its variation depending on the measurement direction. Anisotropy in thermal conductivity is mainly due to the anisotropy of cell structure as shown in Fig. 2. Optical micrographs reveals that cells are elongated along the radial direction. Accordingly, the effective volume fraction of metal phase arranged along the radial direction is much higher than that along the vertical direction. The aspect ratio in the radial direction to the vertical of the elliptical cell is about 2.

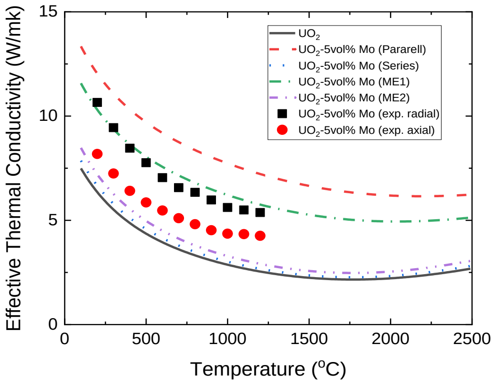

Fig. 1. Thermal conductivity of UO_2-5vol% Mo sample and comparison with basic analytical model values

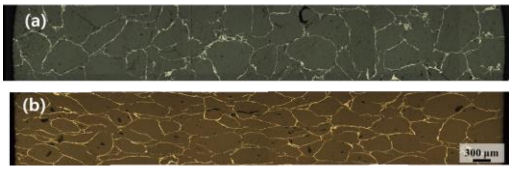

Fig. 2. Pellet microstructures vertical to (a) axial direction and (b) radial direction

2.2 Analytical model for effective thermal conductivity

Effective thermal conductivity of composite is strongly affected by its composition and structure. Numerous analytical models for estimation of effective thermal conductivity of composite materials have been proposed. Many of those models are based on one of the basic structural models of series, parallel, two forms of Maxwell–Eucken and effective medium theory [3]. In order to modeling more complex case, unifying these basic structure models using simple combinatory rules based on structure volume fractions has also been proposed. According to the structural model for composite with multiple continuous phases [4], the effective thermal conductivity (K_e) of composite can be calculated using following analytical equation.

$$K_e = \frac{K_s}{2}\left(\sqrt{1 + 8\,K_p/K_s} - 1\right) \qquad (1)$$

$$K_s = \frac{1}{\sum_{i=1}^{N} \frac{v_i}{k_i}}, \quad K_p = \sum_{i=1}^{N} k_i v_i$$

This model has a simple model solution dependent only on the series (K_s) and parallel (K_p) model values.

Using the equations, we have calculated the effective thermal conductivity of microcell UO_2 and compared with measured values. If the volume contributions are properly adjusted, this analytic model predicts well the measured values as shown in Fig. 3.

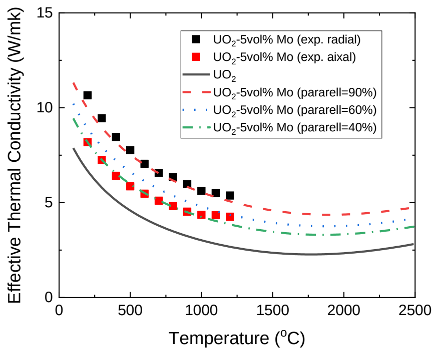

Fig. 3. Comparison of thermal conductivity data with calculated curves using equation (1)

3. FRAPCON type Model for non-irradiated fuel

The analytic model of equation (1) is nor familiar with the typical thermal conductivity model in the FRAPCON code. We have mathematically converted the curves in Fig. 3 into the form of equation in the FRAPCON code.

3.1 UO_2 - Mo

Following equation is the thermal conductivity models of UO_2-xMo (x= *2~10vol%*) as a function of temperature and Mo contents. Fig. 4 shows that the model predicts well the measured data.

$$K_{97\%}(W/mK) = \frac{1}{A' + B' T^{c}} + \frac{E'}{T^2}\exp\left(-\frac{F'}{T}\right) \quad (2)$$

Where,

$$A' = 0.0254 + 1.986\times10^{-2}\exp\left(-\frac{Mo_{vol\%}}{1.6348}\right)$$

$$B' = \frac{7.47\times10^{-4}}{\left(1+\exp\left(-0.94\times\left(Mo_{vol\%}-0.82\right)\right)\right)}$$

$$c = 0.3094\exp\left(-\frac{Mo_{vol\%}}{2.74824}\right) + 0.6925$$

$$E' = 3.5\times10^{9} + 1.664\times10^{8}\,Mo_{vol\%}$$

$$F' = 16124 + 223\exp\left(\frac{Mo_{vol\%}}{8.473}\right)$$

3.2 UO_2 - Cr

Equation (3) is the thermal conductivity model for UO_2-5 vol% Cr microcell pellet.

$$K_{97\%}(W/mK) = \frac{1}{0.021 + 3.13\times10^{-4}\,T^{0.8966}} + \frac{2.85\times10^{9}}{T^2}\exp\left(-\frac{15294}{T}\right) \quad (3)$$

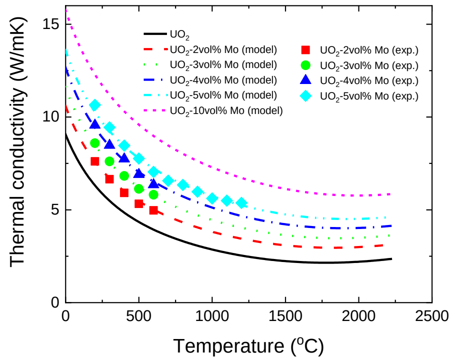

Fig. 4. Comparison of thermal conductivity data with calculated curves obtained using equation (3)

4. Burn-up effect

The effect of UO_2 burnup on effective thermal conductivity of microcell pellet has been estimated based on an assumption that irradiation effect on cell structure and thermal conductivity of metal phase is negligible. Fig. 5 predicted that enhancement of thermal conductivity will be maintained in high burnup.

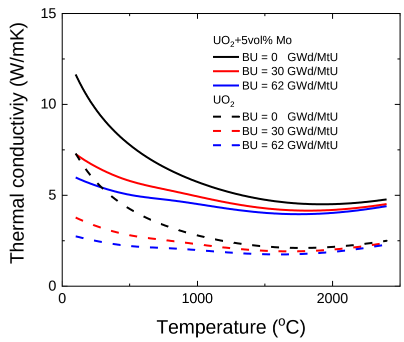

Fig. 5. Estimation of burnup effect on effective thermal conductivity

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