Comparison of thermal resistance models based on the measurement thermal conductivity of the composite fuel pellets

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1. Introduction

To improve the thermal conductivity of nuclear fuels, numerous studies have been conducted on composite nuclear fuels incorporating high thermal conductivity materials [1,2]. In particular, composite nuclear fuels with a metal mesh structure have demonstrated significant improvements in thermal conductivity [3]. These fuels hold promise for applications such as accident tolerant fuels (ATF) and space environments [3,4]. Several methods exist for predicting the thermal conductivity of metal mesh composite nuclear fuels. For example, the effective thermal conductivity can be predicted using methods such as the finite element method [3] or physically based approaches [4,5]. It is well known that the geometry of the network structure has the most significant influence on the thermal conductivity and has been characterized by the aspect ratio (AR). This ratio represents the relationship between the dimensions of the metal structure and the direction of heat transfer [3]. At the same time, the metal content also affected the error tendency between the finite element method (FEM) model and the measurements, resulting in differences in the calculated thermal conductivity between the two-dimensional and three-dimensional models [3]. These variations can be attributed to the different morphologies of the metal mesh encapsulating the UO_2 granules depending on the metal content.

This paper constructs thermal resistance models that account for various metal mesh morphologies and compares them to measurements of UO_2 – 5 vol% Cr microcell pellets. The applicability of these thermal resistance models to composite nuclear fuels with metal mesh structures is investigated.

2. Thermal resistance model design

A 3D unit cubic model with a length of one unit has been proposed to calculate the thermal conductivity of microcells [6]. The effectiveness of this model (referred to as the model 1 in this paper) was demonstrated by successfully calculating the effective thermal conductivity of UO_2 – Mo microcells and UO_2 – Cr microcells [6]. For this study, we developed the model shown in Figure 1 by modifying the structure of the metal mesh. Assuming one-dimensional heat transfer, this model can be represented as a thermal resistance circuit, as shown in Figure 2. Within a unit-length cubic model, the reciprocal of the total thermal resistance is equal to the effective thermal conductivity (Eq (1)).

$$R_{total} = \frac{l}{k_{eff}A} = \frac{1}{k_{eff}} \qquad (1)$$

, where R_{total} is total thermal resistance of unit cubic model (K·m/W), k_{eff} is effective thermal conductivity of unit cubic model (W/m·K), l is heat transfer length (m), and A is cross-section area of heat transfer (m^2). Since the aspect ratio (AR) of the UO_2 - 5 vol% Cr microcell pellet used for comparison is approximately 2, the thermal resistance model for this study was also calculated with an aspect ratio of 2.

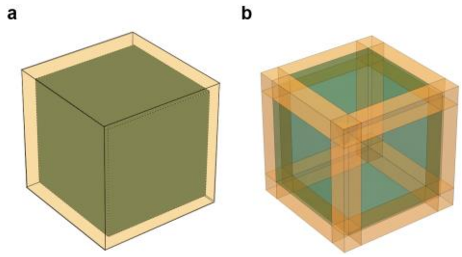

Fig. 1. Schematics of the unit cubic cell models according to the shape at the same metal content of 30 vol% and also AR of 1. The metal structure is (a) completely wrapped around the UO_2 granules (model 2), and (b) in a foamy form (model 3).

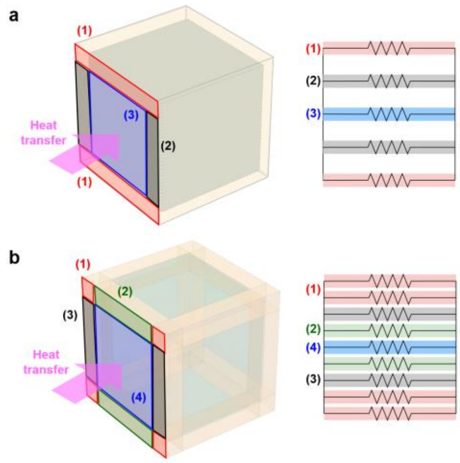

Fig. 2. Thermal resistance circuit diagram on covered metal shape. (a) Metal structure perfectly wrapped around UO_2 granule, (b) Metal structure as form of foam.

3. Results and discussion

Fig. 3 shows the measured thermal conductivity [7] of a UO_2 – 5 vol% Cr microcell pellet at 800˚C along with the corresponding predicted values from the thermal resistance models. Of these models, the model 1 shows the closest thermal conductivity prediction to the measured value. Conversely, the model 2, which is characterized by a metallic structure completely enveloping the UO_2 pellets, has the largest relative error of 5.04%. These results suggest that the metallic structure of the as-fabricated UO_2 – 5 vol% Cr microcells is likely to be partially wrapped around the UO_2 granules.

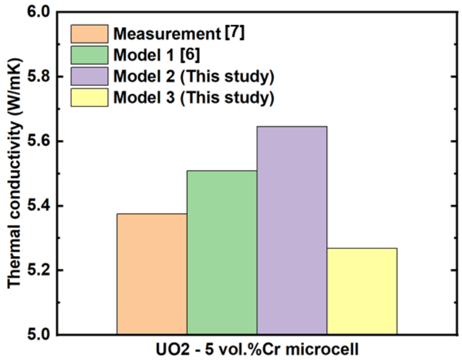

Fig. 3. Comparison of thermal conductivity of UO_2 – 5 vol% Cr microcell pellet on measured value and thermal resistance models.

However, in the case of ceramic-metallic (CERMET) fuel with exceptionally high metal content, Model 2 where the metal structure uniformly surrounds the UO_2 granules resulted in improved thermal conductivity predictions. Figure 4 shows the predicted thermal conductivity of UO_2 – 70 vol% W CERMET. In the temperature range of 400-1400˚C, the results from the physics-based method [4] and Model 2 show strong agreement, with an average error of 2%.

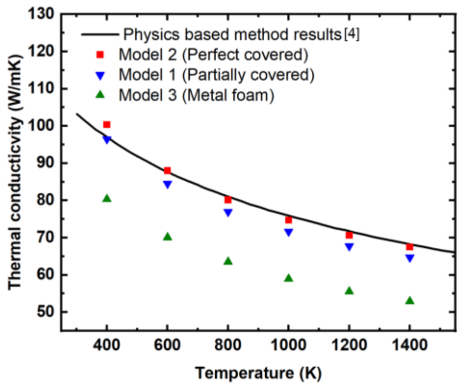

Fig. 4. Thermal conductivities of UO_2 – 70 vol% Mo CERMET fuel. The physics based method results were coming from the reference of [4] and the model 1 was from reference of [6].

4. Conclusion

In this study, thermal resistance circuit models were used to analyze the effect of the shape of the metal structure wrapped around UO_2 granules on the thermal conductivity. For metal microcell pellets with low metal content, models 1 and 3 (involving partially encapsulated UO_2 granules and a metal foam configuration) were found to be suitable for prediction. Conversely, for CERMET fuels with substantial metal content, model 2 showed reduced error.

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REFERENCES

[1] J.H. Yang, K.W. Song, K.S. Kim, Y.H. Jung, A fabrication technique for a UO_2 pellet consisting of UO_2 grains and a continuous W channel on the grain boundary, Journal of Nuclear Materials, Vol.353, p. 202, 2006.

[2] S. Yeo, E. Mckenna, R. Baney, G. Subhash, J. Tulenko, Enhanced thermal conductivity of uranium dioxide – silicon carbide composite fuel pellets prepared by Spark Plasma Sintering (SPS), Journal of Nucler Materials, Vol.433, p.66, 2013.

[3] H.S. Lee, D.J. Kim, S.W. Kim, J.H. Yang, Y.H. Koo, D.R. Kim, Numerical characterization of micro-cell UO_2-Mo pellet for enhanced thermal performance, Journal of Nucler Matterials, Vol.477, p.88, 2016.

[4] J.A. Webb, I. Charit, Analytical determination of thermal conductivity of W-UO_2 and W-UN CERMET nuclear fuels, Journal of Nuclear Materials, Vol.427, p.87, 2012.

[5] J.H. Yang, H.S. Lee, D.S. Kim, D.J. Kim, J.H. Yoon, Y.H. Koo, Mixed analytical model to estimate the anisotropic effective thermal conductivity and in-reactor performance of metallic microcell UO_2, Journal of Nuclear Materials, Vol.585, p.154655, 2023.

[6] H.S. Lee, D.S. Kim, D.J. Kim, J.H. Yang, J.H. Yoon J.H. Lee, Development of thermal conductivity model with use of a thermal resistance circuit for metallic UO_2 microcell nuclear fuel pellets, Nuclear Engineering and Technology, in-press, 2023.

[7] D.J. Kim, K.S. Kim, D.S. Kim, J.S. Oh, J.H. Kim, J.H. Yang, Y.H. Koo, Development status of microcell UO_2 pellet for accident-tolerant fuel, Nuclear Engineering and Technology, Vol.50, p.253, 2018.