Uncertainty Study on Effective Thermal Conductivity of Accident Tolerant Fuel

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1. Introduction

KAERI (Korea Atomic Energy Research Institute) has been developing a micro-cell UO_2 pellet as an accident tolerant fuel (ATF) pellet to enhance the performance and safety of current LWR fuels under normal operating condition as well as during transients/accidents [1-3]. Micro-cell UO_2 pellet, in which all UO_2 grains or granules are covered by thin cell walls of metal, was fabricated by adding Mo metal through a conventional sintering process.

The main purpose of this pellet is to enhance the thermal conductivity of the UO_2 pellet. The metallic micro-cell UO_2 pellet can significantly increase the safety under design basis accidents as well as operating margin under normal operating conditions.

The thermal conductivity of UO_2 pellet is one of the most important properties that influence the fuel operation temperature, in turn, affect directly fuel performance and safety. The modeling of effective thermal conductivity of metallic micro-cell UO_2 pellet was suggested by KAERI[4] to evaluate fuel performance and safety benefits.

The uncertainty of key parameters in thermal conductivity of micro-cell UO_2 pellets may have a significant impact on the fuel operation temperature.

In this paper, we investigated the sensitivity study of the effective thermal conductivity of metallic micro-cell UO_2 pellet using the uncertainty range of the thermal conductivity of UO_2 and metal and metal content. The combined uncertainty study of these parameters on micro-cell UO_2 pellets is also performed to determine the probable effective thermal conductivity ranges using the propagation of uncertainty for parameters.

2. Methods

2.1 Effective thermal conductivity model

The metallic micro-cell UO2 pellet has cell walls in which 5% of Mo metal phases are continuously connected. This pellet has anisotropy in thermal conductivity because the cells are elongated along the radial direction. The effective thermal conductivity of this pellet can be calculated by using the structural model for composite with multiple continuous phases[5]. We have calculated the effective conductivity of micro-cell UO_2 using the following equation (1)[5].

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

where,

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

K_e : Effective thermal conductivity (W/mK)
Ks : Series model
Kp : Parallel model
v_i : Volume fraction of a phase
k_i : Thermal conductivity of a phase (W/mK)
N : Number of phases

The thermal conductivity of UO_2 was calculated by using the modified NFI model[6] with the irradiation effect. In the case of Mo metal, the effect of the irradiation on the thermal conductivity of Mo metal is not well known. For this reason, the irradiation effect of thermal conductivity for Mo metal was not considered for the equation (1). The thermal conductivity of Mo was calculated using the model reported by Abu-Eishah[7].

Fig 1 shows the comparison of calculated effective thermal conductivity of 5 vol% containing micro-cell UO_2 and that of pure UO_2 calculated by the modified NFI model[6].

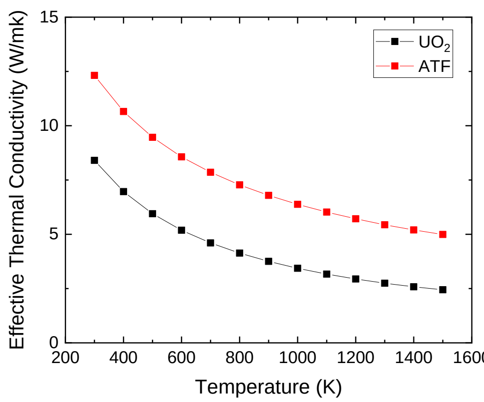

Fig 1. Comparison of thermal conductivity of ATF and pure UO_2 with temperature.

2.2 Uncertainty parameter

The uncertainty study of effective thermal conductivity of micro-cell UO_2 pellet requires the value and the uncertainty of the three parameters: thermal conductivity of UO_2 and Mo and then Mo content.

Table 1 shows the considered parameters and their uncertainty. Thermal conductivity uncertainty of UO_2 and Mo is 10%[6]and 2.35%[7], respectively. The uncertainty of the Mo content was assumed to be 1% in consideration of manufacturing errors.

Table 1. The considered uncertainty parameters

Parameter (unit)	Value[6,7]	Uncertainty[6,7]
UO_2 thermal conductivity (W/mK)	8.4 (300K)	± 10 %
Mo thermal conductivity (W/mK)	135.6 (300K)	± 2.35 %
Mo content (vol%)	5 %	± 1 %

3. Results

3.1 Sensitivity study

The sensitivity study of parameter uncertainty for the effective thermal conductivity of micro-cell UO_2 was investigated by the OAT (one-at-a time) method. Figure 2 and Figure 3 show the effect of individual uncertainty (thermal conductivity of UO_2 and Mo and the content of Mo) on the effective thermal conductivity of micro-cell UO_2, respectively.

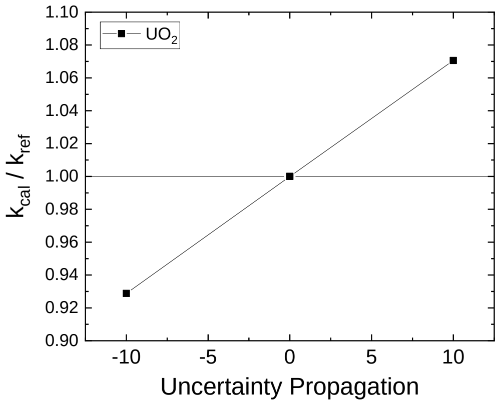

Fig 2. Effective thermal conductivity changes as a function of UO_2 uncertainty propagation.

The sensitivity of the effective thermal conductivity was expressed as the ratio of the calculated value (k_{cal}) to the nominal value (k_{ref}) in the range of uncertainty.

Sensitivity analysis revealed that the UO_2 uncertainty has a more significant influence on the effective thermal conductivity of the microcell UO_2 compared to other parameters. This is because the uncertainty of UO_2 is 10%, which is considerably larger than that of other parameters. If the uncertainty of UO_2 decreases from 10% to 2.35%, it can be seen that the sensitivity of the effective thermal conductivity decreases as shown in the dotted line in Figure 3.

3.2 Combined uncertainty study

The combined uncertainty analysis was performed by using a random sampling method for parameters of the effective thermal conductivity of micro-cell UO_2 pellet. The 10000 random numbers were generated by using a pseudo-random number generator for each parameter and assumed to have a normal distribution. The effective thermal conductivity of micro-cell UO_2 pellet was calculated to use random numbers of three parameters. The combined uncertainty was obtained in the 95% confidence interval for the effective thermal conductivity values calculated by using a random number sampling for parameters and that value is ±6.8%.

This result indicated that the uncertainty of the thermal conductivity of micro-cell UO_2 pellet is smaller than that of pure UO_2 pellet. Since the thermal conductivity of Mo is considerably higher than that of pure UO_2 pellet, combined uncertainty is reduced by this difference.

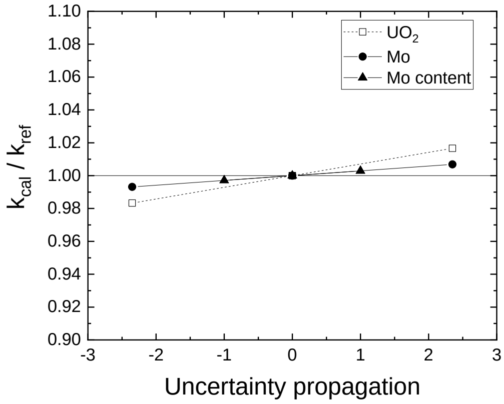

Fig 3. Effective thermal conductivity changes as a function of Mo and Mo content uncertainty propagation.

4. Summary

Sensitivity and combined uncertainty studies based on the uncertainty of parameters have been carried out to determine the uncertainty range of effective thermal conductivity of micro-cell UO_2 pellet.

Understandably, the results show that the uncertainty of the effective thermal conductivity is sensitive to large parameters. Because the difference in thermal conductivity of the two phases (UO_2 and Mo) is quite large, the combined uncertainty based on the effective thermal conductivity model is reduced.

This study is meaningful in evaluating the uncertainty range of micro-cell UO_2 based on the effective thermal conductivity model in the best-estimate analysis.

In the future, in order to more accurately predict the uncertainty of effective thermal conductivity of micro-cell UO_2 pellet, it is necessary to analyze the irradiation effect of the thermal conductivity of Mo, and this will be reflected in the uncertainty evaluation.

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