EVALUATION OF THERMAL CONDUCTIVITY OF SIMULATED INERT MATRIX FUEL

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1 Introduction

One of the nuclear fuel concepts for plutonium burning is uranium-free inert matrix fuel (IMF). Under nuclear reactor operation using 'U-free' inert matrix fuel, plutonium will be not produced. Also, added fissile plutonium will be almost incinerated [1-4].

Inert matrix fuel is composed by means of forming a single or mixed phase. The concept of single phase fuel is based on plutonium embedded in the matrix by a solid solution formation. The concept of mixed phase fuel is constituted in the form of CERCER (ceramics embedded in another ceramics, e.g. $MgAl_2O_4$–$Y_yPu_xZr_{1-y}O_{2-y/2}$), CERMET (ceramics embedded in metal, e.g. Zr–PuO_2) and METMET (metal phase in a metal matrix, e.g. $PuAl_4$–Al) [5].

Matrix materials must satisfy several requirements for physical properties: high melting points, good thermal conductivity, low solubility in the coolant, good compatibility with the cladding, low neutron cross-section, high density, etc. Various inert matrix candidates have been reviewed: Al_2O_3, MgO, $MgAl_2O_4$, CeO_2, Ce_2O_3, Y_2O_3, ZrO_2, $CePO_4$, $ZrSiO_4$, B_4C, SiC, AlN, Mg_3N_2, Si_3N_4, CeN, YN, ZrN, etc [5-7].

In particular, the in-reactor performance, integrity, and safety of nuclear fuel are directly affected by its thermal conductivity. If the thermal conductivity of nuclear fuel can be improved, the fuel performance will be enhanced in various ways. The lower centerline temperature of fuel pellet affects the enhancement of fuel safety as well as fuel pellet integrity during a nuclear reactor operation. In addition, the nuclear reactor power can be uprated due to the higher safety margin. Therefore, the evaluation of thermal conductivity of inert matrix fuel is very important as a nuclear fuel.

In this study, a simulated inert matrix fuel (ZrO_2 ceramic particle dispersed in a Zr metal matrix [8]) was fabricated. Also, for evaluation of thermal conductivity, measurement of the thermophysical properties of the fabricated inert matrix fuel was performed.

2 Experimental and results

A zirconia ceramic particle was used as a surrogate of a plutonium oxide fuel particle. The crystal structures of ZrO_2 and PuO_2 are the same – a cubic fluorite structure. Therefore, zirconia is profitable as a surrogate material for the evaluation of thermal properties. The physical properties of a simulated fuel particle (ZrO_2) were measured (Table 1). The density and size of fuel particle powder were measured by using a gas pycnometer (Micromeritics, AccuPyc II) and a particle size and shape analyzer (QICPIC, Sympatec), respectively.

Zirconia particle powder was simply mixed with zirconium metal powder by using a Turbula mixer. Zr-ZrO_2 powder mixture was compacted and sintered by using a hot press at 800℃ in 20 MPa pressure.

The measured density of the fabricated simulated fuel was 6.008±0.006 g/cc (94.2 %TD). In spite of low reaction temperature, a highly dense sample could be obtained. Figure 1 shows the zirconia particles homogeneously dispersed in a zirconium metal matrix.

For an evaluation of the thermal conductivity of a simulated inert matrix fuel, several thermal properties of simulated fuel were measured. Thermal expansion was measured by using a dilatometer (Netzsch, DIL 402C), and thermal diffusivity was measured by using a laser flash apparatus (Netzsch, LFA-427). Figure 2 shows the simulated inert matrix fuel specimen, which was prepared for thermal diffusivity measurements, and the measured thermal diffusivity as a function of temperature of a simulated fuel is shown in Figure 3.

The measured thermal expansion of simulated fuel as a function of temperature is shown in Figure 4. The measured data was fitted as a function of temperature using a cubic polynomial regression ($\Delta L/L$ (%) $= a + bT + cT^2 + dT^3$), where T is an absolute temperature (K) and T_o is 298 K.

$$\Delta L/L\ (\%) = -2.706\times10^{-1} + 1.05\times10^{-3}T - 4.57\times10^{-7}T^2 + 3.243\times10^{-10}T^3$$

The mean coefficients of linear thermal expansion were calculated using the following equation.

$$\alpha_p(l) = \frac{1}{L_{298}}\left(\frac{dL}{dT}\right)_p$$

The calculated thermal expansion coefficient of simulated fuel is shown in Table 2.

The specific heat of simulated inert matrix fuel was calculated by using literature data and Neumann-Kopp's rule [9, 10]. Figure 5 shows the calculated specific heat of the simulated fuel sample.

The thermal conductivity (k) was calculated by using the following equation,

$$k = Dc_p\rho,$$

where D is the thermal diffusivity, c_p is the specific heat, and ρ is the density as a function of temperature.

The thermal conductivities were normalized to a 95% theoretical density using a modified Loeb equation [11].

The calculated thermal conductivity of the simulated inert matrix fuel based on measured thermal diffusivity and thermal expansion data is shown in Figure 6. The thermal conductivity of fuel was proportional to the temperature. This is a typical tendency of the thermal conductivity of metal.

3 Summary

To evaluate the thermal conductivity of a simulated inert matrix fuel (Simulated IMF), the simulated fuel was fabricated by using hot pressing, and its thermophysical properties were measured and calculated.

The thermal diffusivity and linear thermal expansion of the simulated inert matrix fuel as a function of temperature were measured by using a laser flash method and dilatometry, respectively. Also, the specific heat of the simulated fuel was calculated by using literature data and Neumann-Kopp's rule.

The calculated thermal expansion coefficient of the simulated fuel was 8.93×10^{-6} K^{-1} (R.T.~1073 K). Finally, the calculated thermal conductivity of the fuel based on measured and calculated data was 5.75 W/m-K (averaged at R.T.~1073 K).

4 Acknowledgement

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Table 1. The measured physical properties of simulated fuel particle (ZrO_2).

Density (g/cc)	6.056±0.002
Particle size (mm)	0.341±0.045
Particle aspect ratio	0.97

Table 2. The calculated linear thermal expansion coefficient of simulated fuel.

Composition	Thermal expansion coeff. (K^{-1})
Zr	5.70×10^{-6}
Zr+30 vol.% ZrO_2	8.93×10^{-6} (R.T.~1073 K)
ZrO_2	10.30×10^{-6}

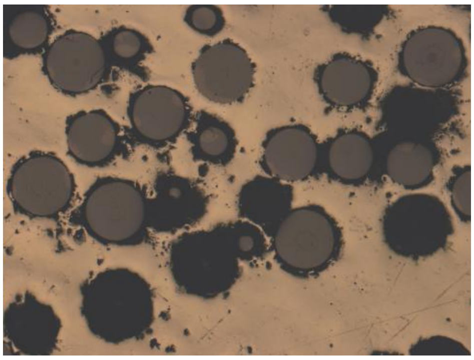

Fig.1. Optical microscopic image of microstructure of simulated inert matrix fuel (×50)

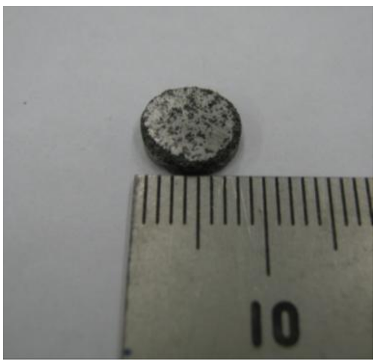

Fig.2. Simulated inert matrix fuel specimen for thermal diffusivity measurement

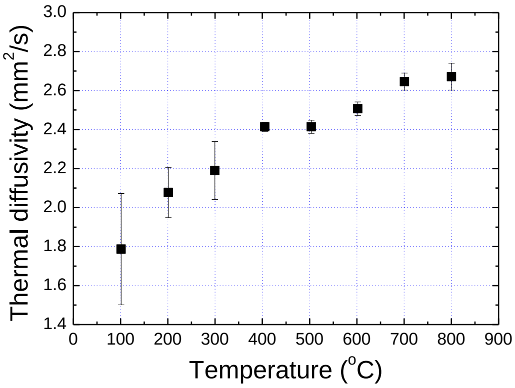

Fig.3. Measured thermal diffusivity of simulated inert matrix fuel

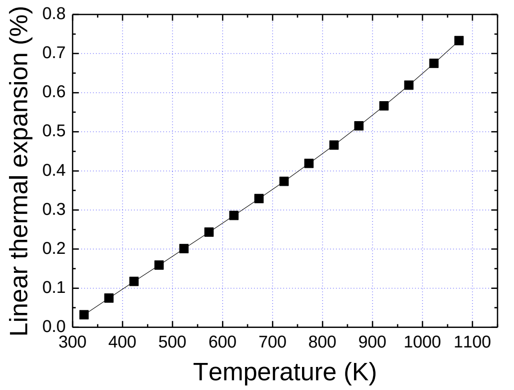

Fig.4. Measured linear thermal expansion of simulated inert matrix fuel

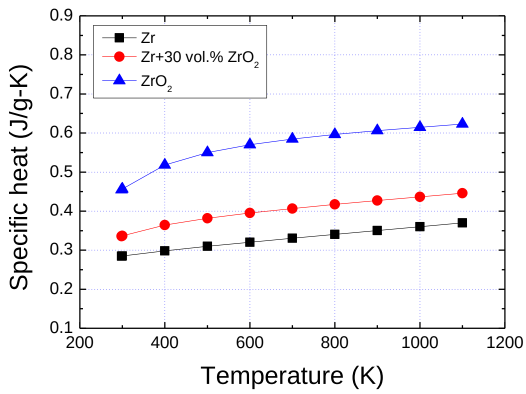

Fig.5. Calculated specific heat of simulated inert matrix fuel

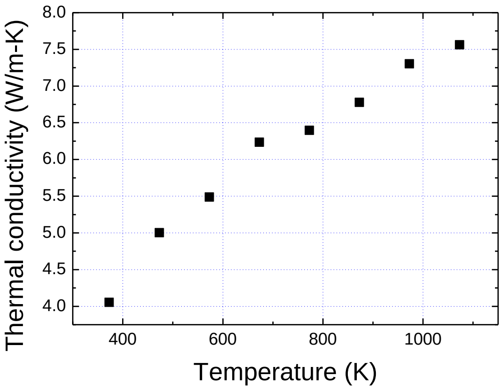

Fig.6. Calculated thermal conductivity of simulated inert matrix fuel based on the measured and calculated data

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