Estimation of Thermal Conductivity for U-Zr Metallic Fuels with Rare Earth Elements

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1. Introduction

The sodium-cooled fast reactor (SFR) is adopted in conjunction with developing the pyroprocessing technology for spent nuclear fuel. In the long run a closed fuel cycle would be accomplished to efficiently manage actinides and reduce a high radioactivity level. The spent fuel is transformed into a new fuel which contains plutonium and minor actinides (MA) along with a carryover of rare earth (RE) elements.

KAERI has developed the technologies for the design and fabrication of U-Zr metallic fuel [1]. In comparison there exists a few works on the fuels containing TRU and RE materials [2-3]. The presence of the foreign constituents such as MA and RE plays a key role in the distribution of the RE-rich phase which in turn affects the fuel performance. In this work, we have investigated the effect of RE on the thermal conductivity of U-Zr fuel.

2. Characteristics of RE in U-Zr

RE with U as well as Zr is nearly completely immicible in the liquid state, and the solubility of RE is extremely low [4]. These characteristics are also applied for U-Zr alloy. For example, the solubility of cerium in U-10Zr alloy is less than 0.5 at% at a higher temperature of 873 K, and Ce-rich precipitates are dispersed in U-Zr matrix [5]. In U-TRU-RE-Zr alloys, the solubility of RE increases somewhat due to the presence of Pu and an addition of RE results in the precipitation of RE-rich phase with an abundant Am content [2].

3. Thermal Conductivity Bounds of Macroscopic Mixtures

Thermophysical properties of metallic fuels for SFR could be varied by the influence of RE-rich second phases. Among these, thermal conductivity is one of the most important parameters dominating the in-reactor performance of fuels.

The analysis here is confined to U-Zr alloys with a heterogeneous RE-rich phase. Keeping in mind that an Au-Ni binary system, which is also almost insoluble with each other, showed no compositional dependence of electrical conductivity [6], the effect of RE elements on the thermal conductivity of U-Zr matrix itself is assumed to be negligible. It is also regarded that RE-rich precipitates are distributed uniformly in the matrix, although it has not been proved from a conventional casting method. Furthermore the thermal resistance at the interface between the matrix and RE-rich phase is neglected.

The effect of the RE precipitates on the effective thermal conductivity is evaluated based on models for the thermal conductivity bounds for heterogeneous materials [7-8]. The upper and lower bounds are calculated by means of the series and parallel models, respectively. Narrower bounds are provided with two forms of the Maxwell models of which type to use is determined by way of choosing the continuous phase. Spheres are considered to be distributed regularly in the matrix. Bruggeman's asymmetric theory extends the range of the Maxwell's equation to the volume fraction of spheres close to one. The shape factor and the orientation factor were derived to account for a deviation from the spherical dispersions [9]. In the case of a second phase randomly distributed with neither phase being necessarily continuous or dispersed, Bruggeman's symmetric theory, so called the Effective Medium Theory (EMT), is applied.

4. Estimation for U-Zr-RE Alloys

Thermal conductivity bounds for U-Zr-RE alloys are estimated by using the models for the macroscopic mixtures. The dependence of thermal conductivity on the temperature and Zr content for U-Zr alloys is available in the literature [10]. Temperature relationships of thermal conductivity are reported for RE such as Ce and Nd [11-12]. These show that thermal conductivity for Ce and Nd fall in the similar range. In the temperature range less than phase transition, thermal conductivity of Ce is around 20% smaller than that of U-Zr fuel.

Material density of the U-Zr-RE alloys is estimated from the density of U-Zr alloy and RE. From the density of the heterogeneous mixture, the volume fraction of RE-rich phase is calculated. With the ratio of thermal conductivity of RE to that of U-Zr, and the volume fraction, thermal conductivity bounds for U-Zr-RE alloys are evaluated. These are performed for six different models for macroscopic mixtures.

Fig. 1 shows the estimated thermal conductivity of U-10Zr-6Ce relative to that of U-Zr as a function of the ratio of the thermal conductivity of Ce normalized to that of U-Zr. It is shown that the series and parallel models serve as lower and upper bounds, respectively. The other models lie in a very narrow range, although there is a slight deviation from such a trend for the Maxwell's model under the assumption of a continuous distribution of the Ce phase.

Fig. 2 shows the estimated thermal conductivity of U-10Zr-6Ce relative to that of U-Zr as a function of the volume fraction of Ce-rich precipitate. Except for extreme bounds, i.e., series and parallel models, it is difficult to discriminate any difference among the thermal conductivities obtained from the other models.

From the figures, the addition of Ce up to 6 wt% is estimated to lower the thermal conductivity of the U-Zr-Ce mixture by less than 5%. It is expected that a similar conclusion can be drawn for an Nd addition.

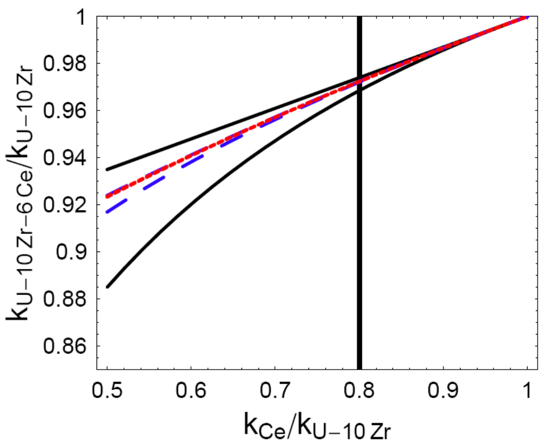

Figure 1. Relative thermal conductivity of U-10Zr-6Ce as a function of relative thermal conductivity of Ce. (upper solid line : parallel, upper long dashed line : Maxwell, upper dotted line : Bruggeman, lower dotted line : EMT, lower long dashed line : Maxwell with continuous Ce phase, and lower solid line : series)

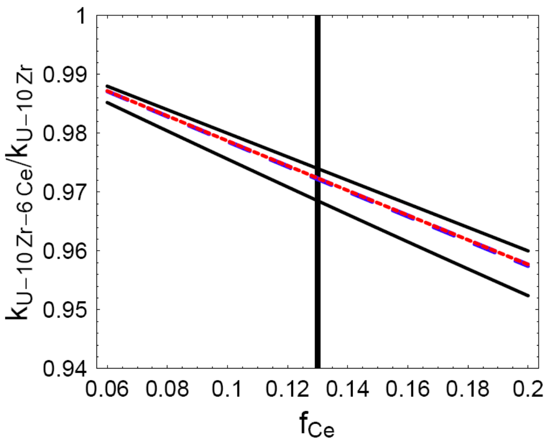

Figure 2. Relative thermal conductivity of U-10Zr-6Ce as a function of volume fraction of Ce.

4. Concluding Remarks

Thermal conductivity of RE-bearing U-Zr fuels was investigated. Under an assumption of a RE-rich phase forming a macroscopic mixture with the matrix, six different models for the thermal conductivity were applied. It was evaluated that the thermal conductivity of the U-Zr fuels would be lowered by less than 5 % due to the addition of RE. In the near future this result will be demonstrated by experiments with U-Zr-RE fuels.

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