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An Estimation of Effective Thermal Conductivity of an Advanced Fuel Element

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1. Introduction

Advanced fuels such as high temperature reactor (HTR) fuel, fully ceramic microencapsulated (FCM) fuel and deep burn-light water reactor (DB-LWR) fuel have a large number of tri-structural isotropic (TRISO) coated fuel particles (CFPs) embedded in their fuel matrix. For a thermal analysis of these fuels, it is necessary to estimate the effective thermal conductivity (ETC) of the fuel pellet or compact which is a mixture of TRISOs and matrix materials.

The ETC of the TRISO fuel compact or pellet has not been accurately measured or known. One possible method to estimate the ETC of the TRISO fuel compact or pellet is to use models derived for predicting the ETC of heterogeneous materials, trying to reduce their inherent uncertainty, limitation of the materials and compositions, empirical parameters, etc. This paper treats the calculation of the ETCs of a fuel and a TRISO using some models derived to express the ETC of the composite and heterogeneous materials.

2. An ETC of a TRISO Fuel

Fig. 1 shows a typical TRISO, which consists of a kernel, a low-density pyrocarbon layer called a buffer, an inner high-density pyrocarbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon (OPyC) layer. Fig. 2 shows an FCM fuel rod which consists of fuel pellets and cladding [1]. The matrix material of an FCM fuel pellet is SiC. The matrix material for an HTR fuel compact and a DB-LWR fuel pellet is graphite.

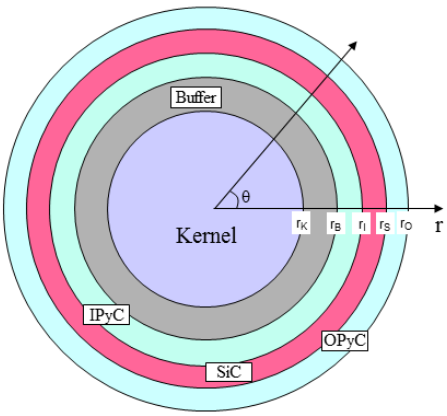

Fig. 1. A TRISO.

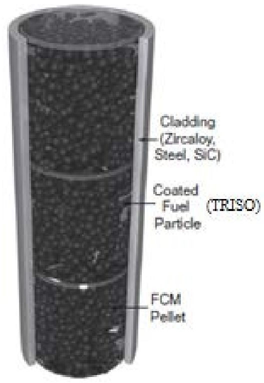

Fig. 2. An FCM Fuel Rod.

Stainsby et al. [2] applied Maxwell's theory to the derivation of the ETC of a multi-layered particle surrounded by a matrix material as follows.

$$k_p = k_m \frac{1-2B_m}{1+B_m}, \tag{1}$$

where k_p is the ETC of a CFP, W/m/K, k_m is the thermal conductivity of a matrix material, W/m/K. If the CFP is a TRISO, B_m can be calculated using the following equation.

$$[M]\{x\} = \{b\}, \tag{2}$$

where

$$[M] = \left[\begin{array}{cccccc|cccccc}
1 & -1 & & & & & \frac{r_O^3}{r_K^3} & -\frac{r_O^3}{r_K^3} & & & & \\
 & 1 & -1 & & & & & \frac{r_O^3}{r_B^3} & -\frac{r_O^3}{r_B^3} & & & \\
 & & 1 & -1 & & & & & \frac{r_O^3}{r_I^3} & -\frac{r_O^3}{r_I^3} & & \\
 & & & 1 & -1 & & & & & \frac{r_O^3}{r_S^3} & -\frac{r_O^3}{r_S^3} & \\
 & & & & 1 & -1 & & & & & 1 & -1 \\
 & & & & & 1 & & & & & & \\
\hline
 & & & & & & 1 & & & & & \\
-k_K & k_B & & & & & 2k_K\frac{r_O^3}{r_K^3} & -2k_B\frac{r_O^3}{r_K^3} & & & & \\
 & -k_B & k_I & & & & & 2k_B\frac{r_O^3}{r_B^3} & -2k_I\frac{r_O^3}{r_B^3} & & & \\
 & & -k_I & k_S & & & & & 2k_I\frac{r_O^3}{r_I^3} & -2k_S\frac{r_O^3}{r_I^3} & & \\
 & & & -k_S & k_O & & & & & 2k_S\frac{r_O^3}{r_S^3} & 2k_O\frac{r_O^3}{r_S^3} & \\
 & & & & -k_O & k_m & & & & & 2k_O & -2k_m
\end{array}\right], \tag{3}$$

$$\{x\} = \{A_K \; A_B \; A_I \; A_S \; A_O \; A_m \mid B_K \; B_B \; B_I \; B_S \; B_O \; B_m\}^T, \tag{4}$$

$$\{b\} = \{0 \; 0 \; 0 \; 0 \; 0 \; 1 \mid 0 \; 0 \; 0 \; 0 \; 0 \; 0\}^T, \tag{5}$$

k_i = the thermal conductivity, W/m/K,
r_i = the radial coordinate, m,
A_i and B_i are unknowns to be solved,

the subscript i indicates K for kernel, B for buffer, I for IPyC, S for SiC, O for OPyC, and m for the matrix.

Folsom [3] suggested that the ETC for a TRISO fuel compact follow the Maxwell and Chiew & Glandt models. The Maxwell model is given by the following form.

$$k_{fuel} = k_m \frac{k_p(1+2\alpha)+2k_m(1-\alpha)}{k_p(1-\alpha)+k_m(2+\alpha)} , \tag{6}$$

where k_{fuel} is the ETC of a fuel compact or pellet, W/m/K, α is a volume fraction of the CFPs, dimensionless. The Chiew & Glandt model is an improved form of the Maxwell model.

$$k_{fuel} = k_m \frac{1+2\beta\alpha+\left(2\beta^3-0.1\beta\right)\alpha^2+0.05\alpha^3 e^{4.5\beta}}{1-\beta\alpha} , \tag{7}$$

where $\beta = (\kappa-1)/(\kappa+2)$, $\kappa = k_p/k_m$. This model matched the experimental data for materials with κ ranging from 10^{-3} to 10^4 and α from 0.15 to 0.85 very well [3].

3. Calculation Results

Table 1 shows the layers of the TRISO used in an FCM fuel and their thicknesses and densities. The enrichment of the uranium nitride (UN) kernel is 19.7 atom %. The considered FCM fuel pellet is a SiC cylinder which is 0.43 cm in diameter, 1 cm in height, and 1.7 g/cm^3 in density. Table 2 indicates the thermal conductivities of TRISO materials and SiC matrix [4-6].

Table 1: Thicknesses and Densities of Layers in a TRISO

Layers	Thickness, μm	Density, g/cm^3
OPyC	20	1.90
SiC	35	3.18
IPyC	35	1.90
Buffer	50	1.05
UN kernel	[a] 800	14.32

[a] This figure means kernel diameter.

Table 2: Thermal Conductivities of TRISO Materials and SiC Matrix

Materials	Thermal Conductivities, W/m/K
UN	$1.864\, e^{-2.14P}\, T^{0.361}$ where P = the porosity (dimensionless) $\in [0,0.2]$ T = the temperature (K) $\in [298,1923]$
Buffer	0.5
PyC	4.0
SiC	$\left(42.58-1.5564\times10^4/T+1.2977\times10^7/T^2-1.8458\times10^9/T^3\right)$ $\cdot 3.91112\times10^{-2} e^{2.24732\times10^{-3}T_{irr}} \cdot (1-P)$ where P = the porosity (dimensionless) T = the temperature (K) T_{irr} = the irradiation temperature (K)
SiC matrix	[a] 7

[a] The most conservative value was chosen among the experimental thermal conductivities of Terrani et al. [6].

Fig. 3 shows the variations of the thermal conductivities of TRISO materials, the ETC of a TRISO calculated using the Maxwell model, the weight-averaged thermal conductivity of a TRISO, and the thermal conductivity of the SiC matrix. The Maxwell-type ETC of a TRISO is about 5.4 W/m/K.

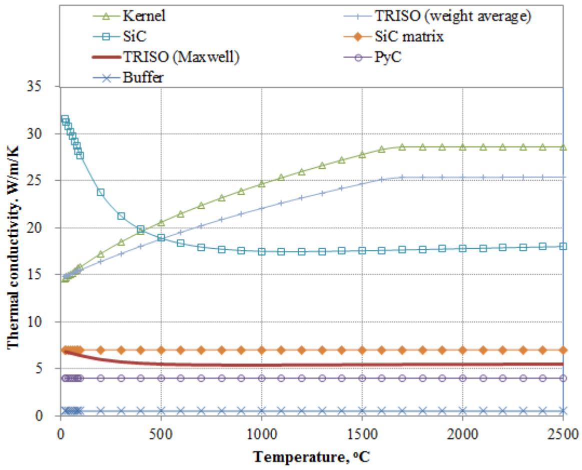

Fig. 3. Thermal Conductivities of TRISO Materials and SiC Matrix

Fig. 4 shows the temperature distribution within a TRISO when the irradiation temperature is 830.6 °C, and the heat generation rate per TRISO is 234 mW. The line "Constant layer TCs" is the right solution for the temperature distribution in a TRISO, which is well described in Ref. [7]. The temperature distribution calculated using the ETC of a TRISO simulates well the heat flux through the coating layers, not the temperature distribution itself. The temperature distribution estimated using the weight-averaged thermal conductivity of a TRISO does not simulate accurately the heat flux through the coating layers and the temperature distribution.

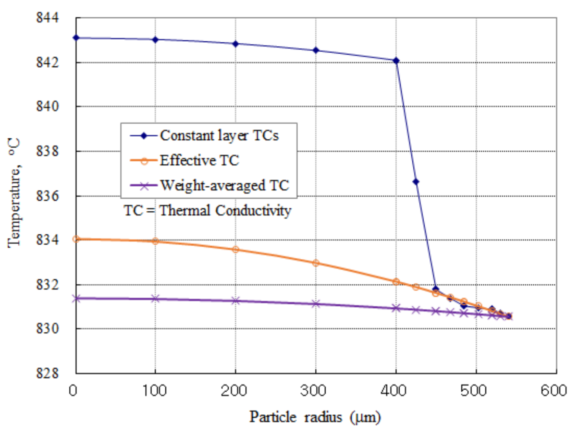

Fig. 4. Temperature Distribution within a TRISO.

Fig. 5 shows the variation of the ETCs of an FCM fuel pellet. The weight-averaged thermal conductivity of all components in a pellet is much higher than the other three types of thermal conductivities. The thermal conductivities following the Maxwell and Chiew & Glandt models are nearly the same. The TRISO can be considered as one particle, the thermal conductivity of which is expressed as an effective value. The ETC of a pellet can then be expressed in the form of the weight average of the thermal conductivities of the particle and matrix. The weight-averaged thermal conductivity is a little bit less than the ETCs following the Maxwell and Chiew & Glandt models.

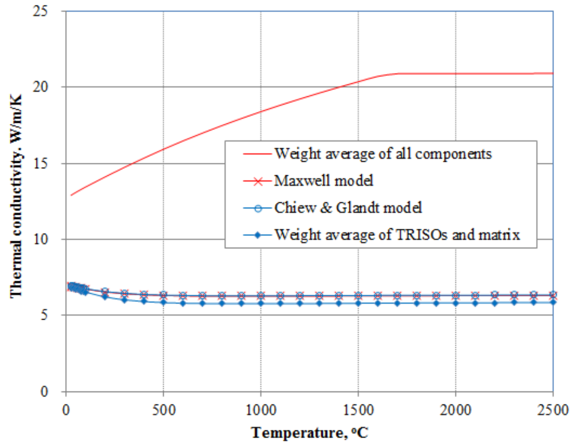

Fig. 5. Effective Thermal Conductivities of an FCM Fuel Pellet.

Fig. 6 shows the temperature distribution within an FCM fuel pellet when the temperature is 607 °C at the pellet surface. The average linear heat generation rate is 177 W/cm. The center pin temperature is about 830 °C when the Maxwell-type thermal conductivity is used. Then, as shown in Fig. 4, the center kernel temperature is about 843 °C at the fuel pin centerline.

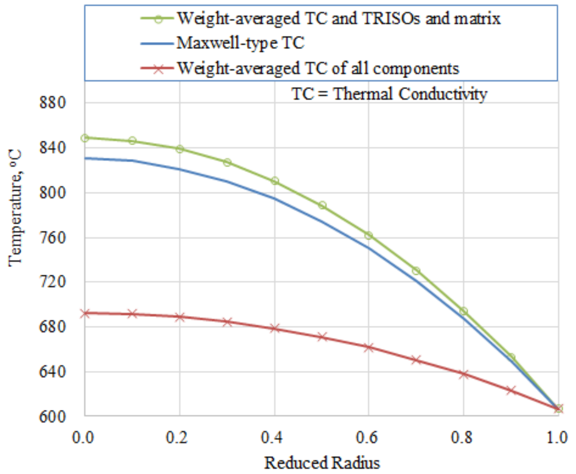

Fig. 6. Temperature Distribution within an FCM Fuel Pellet.

4. Summary

The ETC of a TRISO as one particle follows the Maxwell model. It is not recommended to use the weight average of the thermal conductivities of TRISO materials because the resulting temperature distribution does not simulate the heat flux through the coating layers.

The ETC of a pellet follows the Maxwell and Chiew & Glandt models. It was judged that the weight average of the thermal conductivities of the TRISO and matrix is applicable, but not the weight average of the thermal conductivities of all components of a pellet.

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