Nuclear-Thermal Analysis of Fully Ceramic Microencapsulated Fuel via Two-Temperature Homogenized Model

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1. Introduction

Recently, fully ceramic microencapsulated (FCM) fuel concept has been proposed by Oak Ridge National Laboratory as an accident tolerant fuel (ATF) concept [1, 2]. The FCM fuel is based on a proven safety philosophy that has been utilized operationally in very high temperature reactors (VHTRs). However, the FCM fuel consists of TRISO particles randomly dispersed in SiC matrix. The high heterogeneity in composition leads to difficulty in explicit thermal calculation of such a fuel. Therefore, an appropriate homogenization model becomes essential.

In this paper, we apply the two-temperature homogenized model to thermal analysis of an FCM fuel. The model was recently proposed in order to provide more realistic temperature profiles in the fuel element in VHTRs [3].

2. Two-Temperature Homogenized Model for FCM Fuel

2.1 Two-Temperature Homogenized Model

Fig. 1. shows a heterogeneous FCM fuel as manufactured, in comparison with a homogenized FCM fuel that we would like to construct as a model.

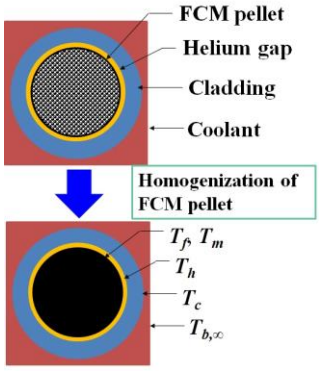

Fig. 1. Two-temperature homogenized model for FCM fuel element

In the homogenized model, FCM pellet region of the fuel element is represented by an imaginary homogeneous media characterized by two temperatures. The medium representing fuel-kernels is to be characterized with thermal conductivity k_f and temperature T_f. Similarly, the medium representing SiC matrix is to be characterized with thermal conductivity k_m and temperature T_m. In order to consider the heat conduction from fuel-kernels to SiC matrix, we introduce a new parameter, μ. We call k_f, k_m, μ as homogenized parameters.

In the homogenized FCM pellet region, we write heat conduction equations for steady-state with homogenized parameters :

$$k_f \nabla^2 T_f - \mu\left(T_f - T_m\right) + q''' = 0, \tag{1}$$

$$k_m \nabla^2 T_m + \mu\left(T_f - T_m\right) = 0, \tag{2}$$

where q''' is homogenized power density determined as :

$$q''' = \frac{\sum_i q'''_{fi} V_{fi}}{V_{pellet}}, \tag{3}$$

q'''_{fi} is power density of i-th fuel kernel and V_{fi} is volume of i-th fuel-kernel and V_{pellet} is volume of pellets.

In the helium gap and SiC cladding, we have :

$$k_h \nabla^2 T_h = 0, \tag{4}$$

$$k_c \nabla^2 T_c = 0, \tag{5}$$

where k_h and k_c are thermal conductivities of helium gap and SiC cladding, respectively.

The interface and boundary conditions are also written as :

i) at the interface between FCM pellet and helium gap,

$$-k_h \nabla T_h = -A_f k_f \nabla T_f - A_m k_m \nabla T_m, \tag{6}$$

where A_f and A_m are the fraction of effective interface areas associated with the fuel-kernel and the SiC matrix, respectively,

ii) at the interface between helium gap and SiC cladding,

$$-k_h \nabla T_h = -k_c \nabla T_c, \tag{7}$$

iii) at the boundary SiC cladding and adjacent to coolant,

$$-k_c \nabla T_c = h(T_{cb} - T_b). \tag{8}$$

2.2 Calculation of Homogenized Parameters

With explicit modeling of TRISO particles in the pellet, we perform Monte Carlo heat conduction calculation using HEATON to obtain the reference heterogeneous solutions [4]. At the same time, after some algebra, we can obtain analytic solutions for Eqs. (1), (2), (4) and (5), as follows :

$$T_m(r) = c_1 \frac{I_0(\sqrt{A}r)}{A} - \frac{B}{4A} r^2 + c_4, \tag{8}$$

$$T_f(r) = -\frac{k_f}{\mu}\left[c_1 I_0(\sqrt{A}r) - \frac{B}{A}\right] + T_m(r), \tag{9}$$

$$T_h(r) = c_5 \ln r + c_6, \tag{10}$$

$$T_c(r) = c_7 \ln r + c_6, \quad (11)$$

where

$$A = \frac{\mu\left(k_f + k_m\right)}{k_f k_m} > 0, \quad B = \frac{\mu q'''}{k_f k_m} > 0, \quad (12)$$

and the unknown coefficients c_1, c_4, c_5, c_6, c_7 and c_8 are determined by applying i) convective boundary condition at the cladding surface, ii) continuity of heat flux from $T_f(r)$, $T_m(r)$ to $T_h(r)$ at the pellet surface, iii) continuity of $T_m(r)$ and $T_h(r)$ at the pellet surface and iv) continuity of $T_h(r)$ and $T_c(r)$ at the gap surface [3]. The next step is a procedure to determine the homogenized parameters k_f, k_m and μ. The idea is to match Eqs. (8) and (9) with solutions of HEATON calculation. The way to match the two solutions is through the least squares of the difference between the two solutions in the pellet, i.e., the procedure is to find k_f, k_m, μ that minimize the following functional expression :

$$F\left(k_f, k_m, \mu\right) = \sum_i \left[T_{f,i} - T_{f,i}^{MC}\right]^2 + \sum_j \left[T_{m,j} - T_{m,j}^{MC}\right]^2, \quad (13)$$

where i, j are Monte Carlo tally indices.

3. Numerical Results

FCM fuel configuration is shown in Table I and II [2, 5]. Power per TRISO particle is 400 mW [2]. Packing fraction of the pellet is 0.388 and coolant bulk temperature is set to 570 K. Reference solution is obtained from the HEATON Monte Carlo code [4].

Table I. FCM fuel pellet configuration

Layer	Radius (cm)	Thermal conductivity (W/cmK)
Kernel	0.0425	0.02
Buffer	0.0475	0.005
Inner PyC	0.0510	0.04
SiC	0.0545	0.1
Outer PyC	0.0580	0.04
SiC matrix	0.0580	0.1

Table II. FCM fuel element configuration

Layer	Radius (cm)
Pellet	0.4095
Helium gap	0.4180
Cladding	0.4750
Pitch	1.26

Homogenized parameters, A_f and homogenized power density (q''') are shown in Table III. The two-temperature homogenized model is calculated by finite element method (FEM) with 4,950 triangular elements and quadratic shape function. Temperature profiles are shown in Figs. 2 and 3. In Fig. 3, the homogenized model solutions are in excellent agreement with the heterogeneous Monte Carlo calculations.

Table III. Homogenized parameters, A_f and q'''

Parameters	Value
k_f (W/cmK)	0.00412
k_m (W/cmK)	0.04032
μ (W/cm^{3}K)	7.6717
A_f	0.18
q''' (W/cm^3)	189.82

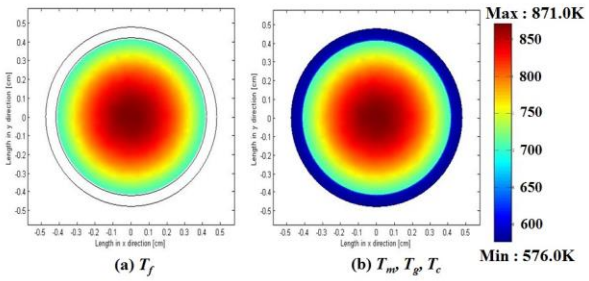

Fig. 2. Radial temperature profiles of FCM fuel

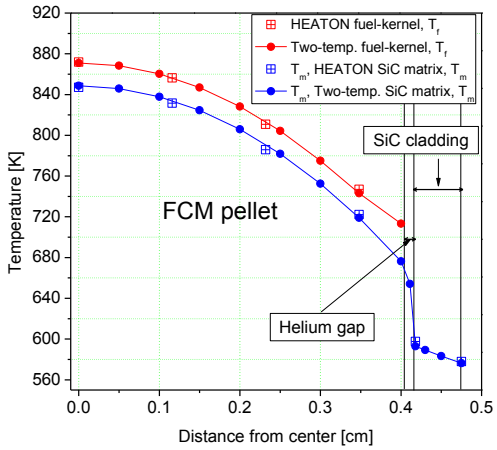

Fig. 3. Comparison of temperature profiles with HEATON results

4. Conclusions

We applied the two-temperature homogenized model to FCM fuel. The two-temperature homogenized model was obtained by particle transport Monte Carlo calculation applied to the pellet region consisting of many coated particles uniformly dispersed in SiC matrix.

Since this model gives realistic temperature profiles in the pellet (providing fuel-kernel temperature and SiC matrix temperature distinctly), it can be used for more accurate neutronics evaluation such as Doppler temperature feedback. The transient thermal calculation may be performed also more realistically with temperature-dependent homogenized parameters in various scenarios.

References

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