Proceedings of the Reactor Physics Asia 2015 (RPHA15) Conference
Jeju, Korea, Sept. 16-18, 2015

Nuclear-Thermal Analysis of Fully Ceramic Microencapsulated Fuel with Randomly Dispersed TRISO Particles via Two-Temperature Homogenized Model

Yoonhee Lee and Nam Zin Cho*
Korea Advanced Institute of Science and Technology
291 Daehak-ro,Yuseong-gu, Daejeon, Korea 34141
*Corresponding author: nzcho@kaist.ac.kr

1. Introduction

As an accident tolerant fuel (ATF) concept, fully ceramic microencapsulated (FCM) fuel concept has been proposed recently after the Fukushima Daiichi reactor accident in Japan [1].

The FCM fuel consists of TRISO particles randomly dispersed in a SiC matrix, which is a similar configuration to a fuel in the VHTRs. For thermal analysis of the fuel elements in the VHTRs, volumetric-average thermal conductivity model was used [2]. However, this model is not conservative in that thus obtained temperature profiles are lower than the real values. Moreover, it is unable to distinguish fuel-kernel and matrix temperatures.

For the thermal analysis of the research reactor fuels, where nuclear fuel particles are randomly dispersed in the matrix, a modified Hashin and Shtrikman correlation is used [3, 4]. It is based on the effective medium theory that pertains to analytical modeling to describe the macroscopic properties of composite materials. Since the model was developed for the composite materials consisting of two constituent materials, it cannot be applied to the FCM fuel having TRISO particles.

Recently, a method for homogenization of thermal conductivities in the compact and block type fuels in the VHTRs was proposed [5]. This work is based on a two scale asymptotic expansion method. It gives more realistic temperature profiles than those from volumetric-average model. However, this model is applicable to the fuels having a periodic structure, and may not be applicable to the fuels in which TRISO particles are randomly distributed.

We have proposed a two-temperature homogenized model for randomly distributed TRISO fuels, using particle transport Monte Carlo method for heat conduction problem [6], and applied to the thermal analysis of VTHR fuel element [7] and the FCM fuel element [8, 9]. In the model, we can distinguish the fuel-kernel and SiC matrix temperatures. Moreover, the temperature profiles obtained are more realistic than those from volumetric-average model. In the previous works [8, 9], the authors applied the model to the FCM fuels in which TRISO particles are distributed in the coarse lattice centered structure (CLCS) [10].

In this paper, we will apply the two-temperature homogenized model to the FCM fuel element in which TRISO particles are randomly distributed in the fine lattice structure (FLS) [10]. The results are compared to those of harmonic- and volumetric-average thermal conductivity models.

2. Two-Temperature Homogenized Model for the FCM Fuel Element

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.

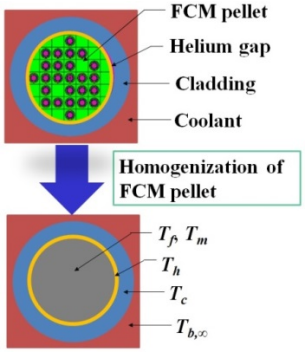

Fig. 1. Two-temperature homogenized model for the FCM fuel element

In the homogenized model, FCM pellet region of the fuel element is represented by an imaginary media characterized by two temperatures. The medium representing fuel-kernels is to be characterized by 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, 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 :

$$k_h \nabla^2 T_h = 0, \quad (4)$$

$$k_c \nabla^2 T_c = 0, \quad (5)$$

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,

$$-k_h \nabla T_h = -A_f k_f \nabla T_f - A_m k_m \nabla T_m, \quad (6)$$

where A_f and A_m are the fraction of effective interface areas associated with the fuel-kernel and the SiC matrix, respectively. The area fractions in Eq. (6) involve an elusive concept, other than their summation being unity. In this study, we assumed that effective interface areas for the fuel-kernels and the SiC matrix are proportional to 2/3 of each volume of fuel-kernels and the SiC matrix in the pellet. Sensitivity studies for typical packing fractions show that temperature profiles in the pellet are not affected significantly by the values of A_f.

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

$$-k_h \nabla T_h = -k_c \nabla T_c, \quad (7)$$

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

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

2.2 Calculation of the Homogenized Parameters

With explicit modeling of the randomly distributed TRISO particles in the heterogeneous fuel element, we perform heat conduction calculation via Monte Carlo method using the HEATON program to obtain the reference solution [6, 11]. At the same time, after some algebra, we can obtain analytic solutions for Eqs. (1), (2), (4), and (5), as follows :

$$T_m(r) = c_1 \frac{I_0(\sqrt{A}r)}{A} - \frac{B}{4A} r^2 + c_4, \quad (9)$$

$$T_f(r) = -\frac{k_f}{\mu}\left[c_1 I_0(\sqrt{A}r) - \frac{B}{A}\right] + T_m(r), \quad (10)$$

$$T_h(r) = c_5 \ln r + c_6, \quad (11)$$

$$T_c(r) = c_7 \ln r + c_6, \quad (12)$$

where

$$A = \frac{\mu(k_f + k_m)}{k_f k_m} > 0, \; B = \frac{\mu q'''}{k_f k_m} > 0, \quad (13)$$

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 [7]. The idea is to match Eqs. (9) and (10) 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 :

$$F(k_f, k_m, \mu) = \sum_i \left[T_{f,i} - T_{f,i}^{MC}\right]^2 + \sum_j \left[T_{m,j} - T_{m,j}^{MC}\right]^2, \quad (14)$$

where i, j are Monte Carlo tally indices.

3. Numerical Results

FCM fuel configuration in which TRISO particles are randomly dispersed is shown in Fig. 2. Geometric and thermal properties of the FCM fuel element are shown in Tables I and II [12-14]. Random distribution of the TRISO particles is generated by the HEATON program [11]. Power per TRISO particle is 423mW. Packing fraction of the pellet is 0.361 and coolant bulk temperature is set to 570 K. Reference solution is obtained from the HEATON program [11].

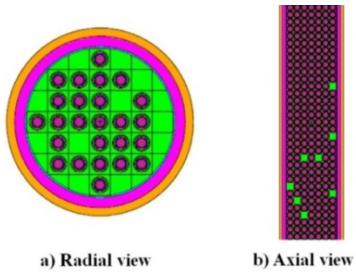

Fig. 2. HEATON modeling of the FCM fuel element

Table I. FCM fuel pellet configuration

Layer	Radius (cm)	Thermal conductivity (W/cmK)
Kernel	0.0425	0.309
Buffer	0.0475	0.005
Inner PyC	0.0510	0.04
SiC	0.0545	0.09
Outer PyC	0.0580	0.04
SiC matrix	0.05801	0.09

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, A_m and homogenized power density (q''') are shown in Table III. The two-temperature homogenized model is calculated by finite element method (FEM) with 4950 triangular elements and quadratic shape function.

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

Parameters	Value
k_f (W/cmK)	0.00166
k_m (W/cmK)	0.05891
μ (W/cm^{3}K)	7.6706
A_f	0.07
A_m	0.93
q''' (W/cm^3)	189.82

The resulting temperature profiles are shown in Figs. 3

and 4. The temperature profiles from the harmonic-(HATC) and volumetric-average thermal conductivity models (VATC) are compared in Fig. 5. In Fig. 4, the homogenized model solutions are in excellent agreement with the HEATON calculation.

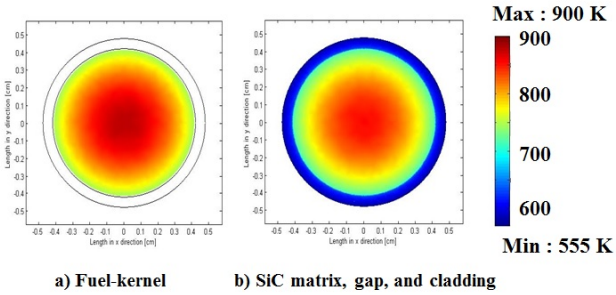

Fig. 3. Radial temperature profiles of FCM fuel via the two-temperature homogenized model

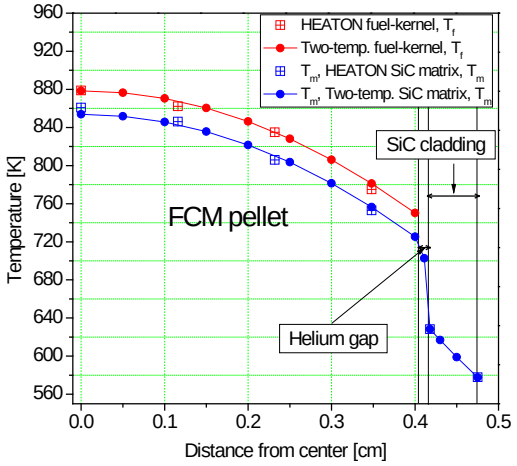

Fig. 4. Comparison of the temperature profiles with HEATON results

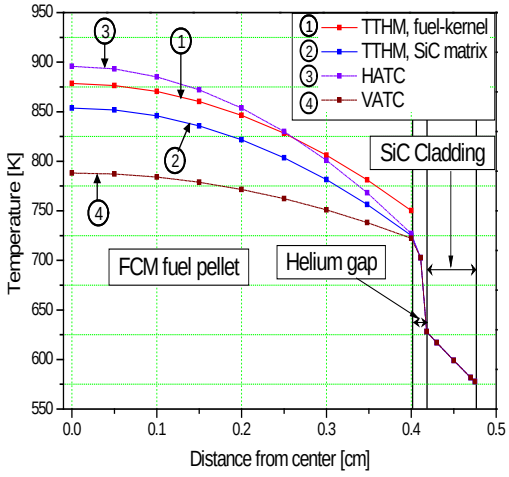

Fig. 5. Comparison of the temperature profiles with those from the harmonic-and volumetric-average thermal conductivity models

Note that difference in the maximum temperatures between the two-temperature homogenized model and the harmonic-average thermal conductivity model is ~15 K. The difference between the two-temperature homogenized model and the volumetric-average thermal conductivity model is ~90 K.

4. Conclusions

In this paper, we applied the two-temperature homogenized model to the FCM fuel in which TRISO particles are randomly dispersed. The two-temperature homogenized model for the FCM fuel was obtained by the particle Monte Carlo calculation applied to the pellet region consisting of TRISO particles randomly dispersed in the SiC matrix. The Monte Carlo calculation was done by the HEATON program. The two-temperature homogenized model shows excellent agreement with the results from the HEATON calculation.

The two-temperature homogenized model gives ~15 K lower maximum temperatures than that from the harmonic-average thermal conductivity model, and ~90 K higher maximum temperature than that from the volumetric-average thermal conductivity model. Since the two-temperature homogenized model showed excellent agreement with the heterogeneous calculations of the FCM fuel element, we can say that the temperature profiles provided by the two-temperature homogenized model are more realistic.

References

1. Terrani K. A. et al., J, "Fully Ceramic Microencapsulated Fuels for LWRs, invited," *Trans. Am. Nucl. Soc*., **106**, 1106 (2012).
2. Kadak A. C., "Modular Pebble Bed Reactor Project University Research Consortium Annual Report," INEEL.EXT-200-01034, MIT-ANP-RP-075, Idaha National Engineering & Environmental Laboratory, MIT (2000).
3. Hashin J. and Shtrikman S., "A variational approach to the theory of the effective magnetic permeability of multiphase materials," *J. Appl. Phys*, **33**, 3125 (1962).
4. Marelle V., Huet F., and Lemoine P., "Thermo-mechanical modeling of U-Mo fuels with MAIA," *8th Inter. Mtg. in RRFM*, Munich, Germany, March 21-24, 2004, European Nuclear Society (2004).
5. Chang J., "Homogenization of thermal conductivity in a periodic structure," *Proc. Korean Nuclear Society Spring Meeting*, Jeju, Korea, May 5-7, 2015, Korean Nuclear Society (2015).
6. Cho N. Z., "Particle Transport Monte Carlo Method for Heat Conduction Problems," in *Heat Conduction – Basic Research*, Chapter 13, InTech, Rijeka, Croatia (2011), accessed by http://www.intechopen.com/books/heat-conduction-basic-research/
7. Cho N. Z. et al., "Two-Temperature Homogenized Model for Steady-State and Transient Analyses of a

Pebble with Distributed Fuel Particles," *Ann. Nucl. Energy*, **36**, 448 (2009); see also Corrigendum *Ann. Nucl. Energy*, **37**, 293 (2010).

8. Lee Y. and Cho N. Z., "Three-dimensional single-channel thermal analysis of fully ceramic microencapsulated fuel via two-temperature homogenized model," *Ann. Nucl. Energy*, **71**, 254 (2014).
9. Lee Y. and Cho N. Z., "Steady- and transient-state analyses of fully ceramic microencapsulated fuel loaded reactor core via two-temperature homogenized thermal-conductivity model," *Ann. Nucl. Energy*, **76**, 283 (2015).
10. Yu H. and Cho N. Z., "Comparison of Monte Carlo Simulation Models for Randomly Distributed Particle Fuels in VHTR Fuel Element," *Trans. Am. Nucl. Soc*., **95**, 719 (2006).
11. Song J. H. and Cho N. Z., "HEATON – A Monte Carlo Code for Thermal Analysis of Pebble Fuels in VHTRs," NURAPT-2007-01, Nuclear Reactor Analysis and Particle Transport Laboratory (NURAPT), Korea Advanced Institute of Science and Technology (2007).
12. Brown N. R. et al., "Neutronic Evaluation of a PWR with Fully Ceramic Microencapsulated Fuel, Part I: Lattice Benchmarking Cycle Length, and Reactivity Coefficients," *Ann. Nucl. Energy*, **62**, 538 (2013).
13. Terrani K. A. et al., "Progress on matrix SiC Processing and properties for fully ceramic microencapsulated fuel form," *J. Nucl. Mat.*, **457**, 9 (2015).
14. Ross R. B. et al., "Thermal conductivity correlation for uranium nitride fuel between 10 and 1923 K," *J. Nucl. Mat*, **151**, 313 (1988).