The Effects of TRISO Particle Distribution on Thermal Behavior of Fully Ceramic Microencapsulated Fuel

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ABSTRACT

To assess the applicability of Fully Ceramic Microencapsulated (FCM) to a commercial reactor, modeling of FCM and TRISO particles and detailed behavior analyses are required. In particular, it is necessary to quantitatively evaluate the uncertainty due to the non-uniform TRISO particle distribution. In this study, the model to evaluate the thermal behavior of FCM and TRISO particles has been developed based on finite element analysis. It is confirmed that the radial temperature shows symmetric distribution with kernel radius size from 300 to 400 microns for packing fraction of 40%. Also, thermal conductivity degradation of FCM fuel by irradiation has largest impact on fuel temperature.

1. Introduction

After the Fukushima accident, various Accident Tolerant Fuels have been developed globally. Among the several candidates for fuel concept, Fully Ceramic Microencapsulated (FCM) fuel is considered as promising material due to its high strength and high thermal conductivity. Various researches about the basic performance analysis and fabrication process are in progress [1]. Especially, several researches have been performed to assess the applicability of FCM into PWR. These are mainly focused on nuclear feedback calculation [2] or safety analysis [3] of core. In these analyses, the non-uniformity of TRISO particles in the FCM is modeled by using homogenized model. However, more realistic thermal model is required to evaluate further mechanical analysis Therefore, a thermal model for FCM fuel has been developed with consideration of random distribution of TRISO particles.

2. Analysis

2.1 Modeling

A model has been proposed for the realistic thermal behavior analysis of FCM and TRISO particles. In order to simplify the complex structure of FCM, two step analyses are performed based on Finite Element Method. In the first step, thermal analysis with homogenized material properties is performed. The homogenization method is useful for estimating effective physical properties of multi-components with certain degree of error. Since the diameter of TRISO particle is considerably smaller than the FCM pellet, TRISO particles are assumed as point heat sources. Figure 1 shows mesh generation and algorithm for generating random particle distribution pattern of TRISO particles. In the second step, thermal analysis with heterogeneous material properties is performed. Unlike the first step, the second step is required to analyze the thermal behavior of TRISO particle which is consist of several coating layers and its surroundings. To give appropriate boundary conditions in thermal analysis, calculated temperature results from first analysis step are used. Note that the analysis in this step is performed with real dimension and material properties of coating layers and kernel.

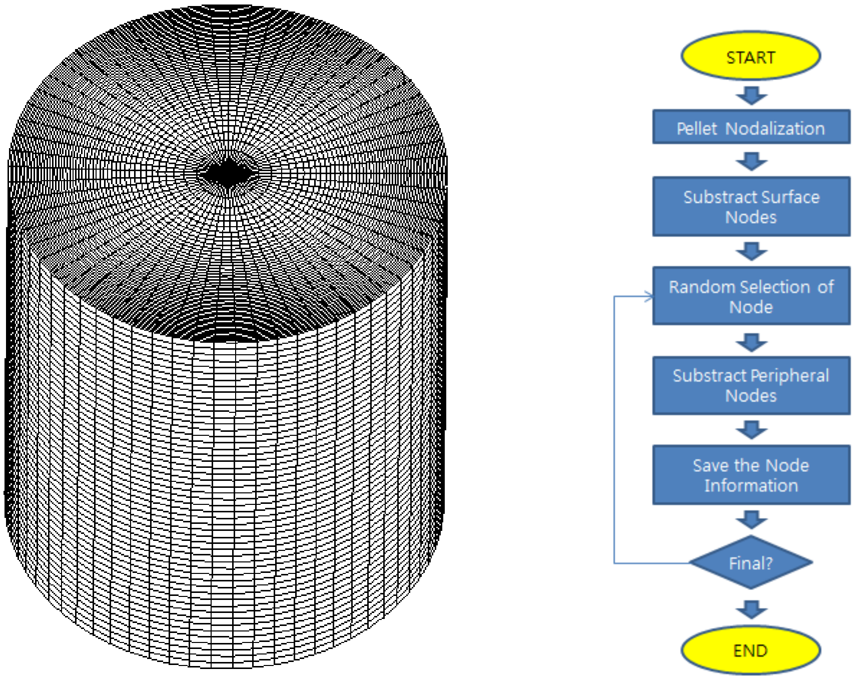

Fig 1. Mesh Generation and Random Node Selection Algorithm

2.2 Test Case

In this analysis, fuel rod geometry conditions of PWR 16x16 fuel assembly type are used with fuel surface temperature of 700K. Linear heat generation rate is assumed as 10 kW/ft. The thicknesses of buffer, Inner PyC, SiC and Outer PyC layers of TRISO particle are assumed to be fixed 50, 35, 35 and 20 microns, respectively. Uranium Nitride is considered as kernel material.

In the analysis, the kernel radius size is varied from 300, 350 to 400 microns. Also, to analyze the behavior according to packing fraction, packing fraction is varied from 40, 45 to 50%. As the thermal conductivity of SiC has been reported to decrease with burnup, thermal conductivity degradation cases are also added. Finally, the effects of various pattern are evaluated by using 10 different particle distribution patterns.

3. Results and Discussion

3.1 Kernel Size Effects

Figure 2 shows the axial and radial temperature distributions according to kernel radius 300, 350 and 400 microns with packing fraction of 40%. The gray color near the centerline of FCM means the temperature exceeding the range of legend. Temperature distribution appears to be almost symmetrical in the axial and circumferential directions, even though there is some irregularity due to the TRISO particles.

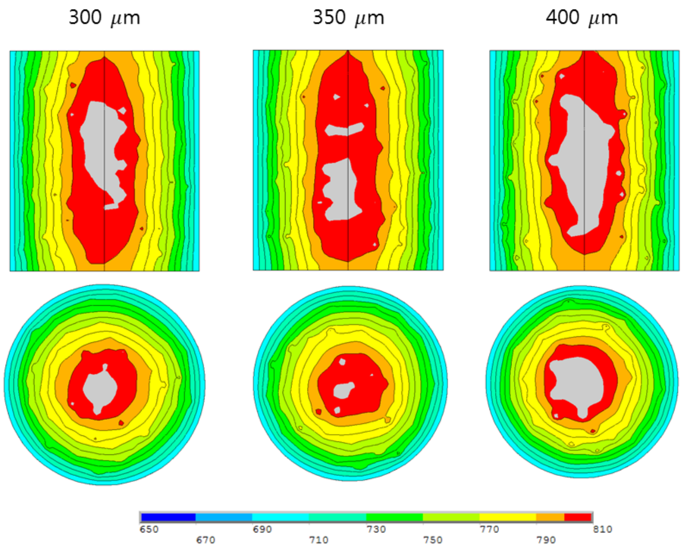

Fig 2. Particle Size Effects on Fuel Axial/Radial Temperature

3.2 Packing Fraction Effects

As the packing fraction increases, more symmetric temperature distribution is expected because the power of each particle is lowered and non-uniformity is resolved. This prediction is confirmed through the analysis results of Figure 3. In the packing fraction 40%, there is more non-homogeneous of temperature in axial and radial direction. But by increasing packing fraction, axial and radial homogeneous temperature region is generated. Also, In the case of PF 50%, it can be seen that this region is further enlarged in the axial direction.

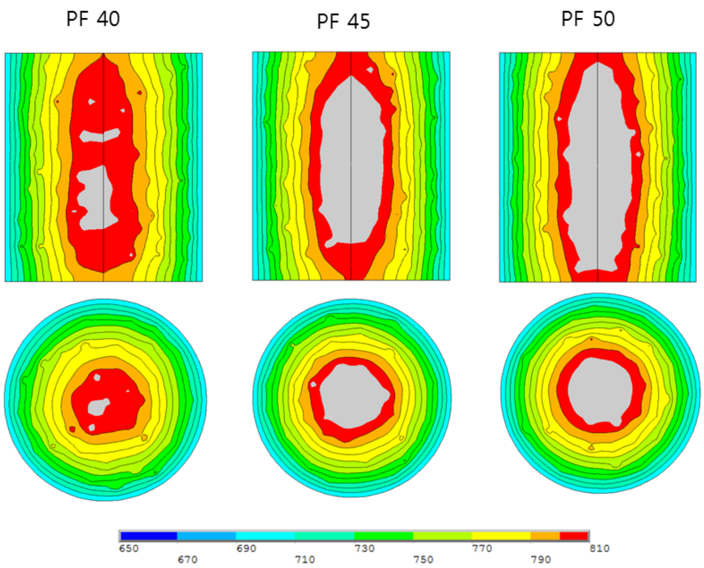

Fig 3. Packing Fraction Effects of Fuel Axial/Radial Temperature

3.3 Thermal Conductivity Effects

Figure 4 shows the temperature distribution with different thermal conductivity. In this analysis, constant thermal conductivity which is corresponding to pellet average temperature and degraded FCM thermal conductivity [3] are used. When we consider the thermal conductivity degradation of FCM, temperature is almost increased in 65 K compared to constant thermal conductivity case. This implies that FCM fuel thermal conductivity degradation by irradiation is significant in temperature analysis.

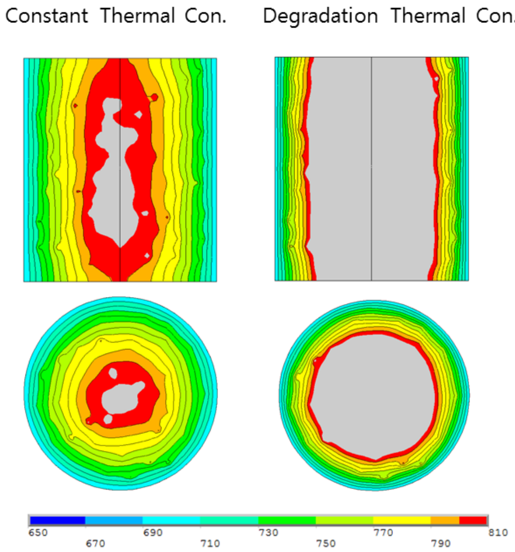

Fig 4. Thermal Conductivity Effects on Fuel Axial/Radial Temperature

3.4 Distribution Pattern Effects

To identify the effect of TRISO particle distribution pattern on thermal behavior, 10 different patterns are generated by using random node selection algorithm and thermal analyses are performed. The maximum temperature deviation of the centerline within 10 test cases is 12.6K. Also, distribution of particles in axial direction causes temperature distribution in axial direction in all cases. In the Pattern 7, temperature differences between axial pellet center and upper/lower position are about 25K.

Table 1 shows the statistics for the positions of the particles. From the averaged radial position of particles statistics, it is confirmed that the distribution of TRISO particles in radial direction affects the temperature. Figure 5 shows the comparison results between the Pattern 6 and the Pattern 7, where the particles are most concentrated in the center and outer. The particle distribution can have effect on FCM temperature. Namely, the center positioned particle increases the centerline temperature. On the contrary, the more the particles are located in the periphery, the lower the centerline temperature.

Pattern	Radial Position		Axial Position	
	Average (m)	Skewness	Average (m)	Skewness
1	0.00251	-0.57553	0.00476	-0.00163
2	0.00250	-0.55383	0.00473	0.01736
3	0.00253	-0.59920	0.00470	0.03194
4	0.00250	-0.56191	0.00476	-0.00627
5	0.00253	-0.60932	0.00472	-0.00100
6	0.00254	-0.61553	0.00476	-0.02122
7	0.00249	-0.57947	0.00473	0.00479
8	0.00250	-0.53523	0.00473	0.01298
9	0.00250	-0.58429	0.00476	-0.01772
10	0.00252	-0.59506	0.00474	0.01029

Tab 1: Particle Distribution Pattern Statistics

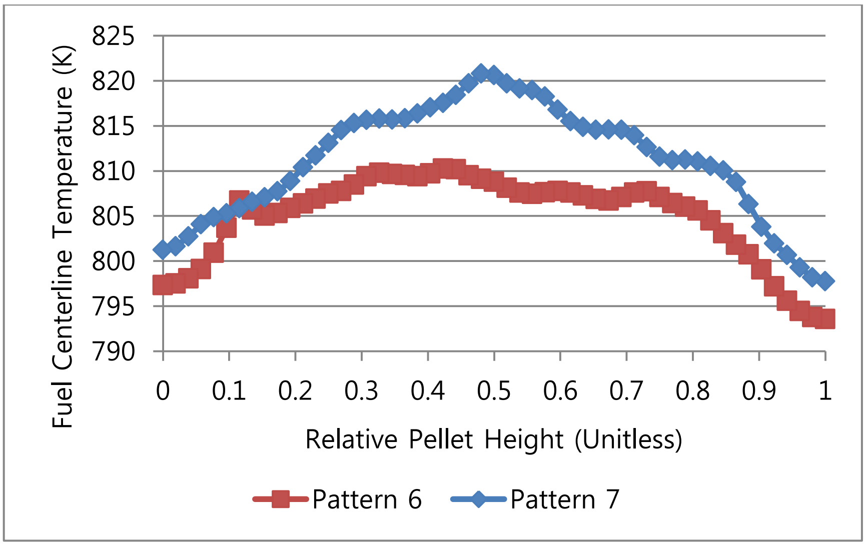

Fig 5. Particle Distribution Pattern Effect on Fuel Centerline Temperature

3.5 Temperature Field around TRISO Particle

Figure 6 shows the temperature fields around TRISO particle located in mid and outer pellet radius positions. And Figure 7 shows boundary temperature of TRISO coating layers. Because there is temperature gradient in the radial direction, the position of maximum temperature within TRISO particle is shifted to closer position to pellet centerline. The shifted amount is 125 microns in mid radius position and 220 microns in outer radius position. Since the thermal conductivity of the UN is high, the temperature different between kernel surface and the maximum temperature is small. If we use kernel material as UO_2 instead of UN, there will be more large temperature gradient in TRISO particle. Therefore, temperature gradient induced amoeba effect of fuel kernel phenomenon can be reduced by using UN kernel.

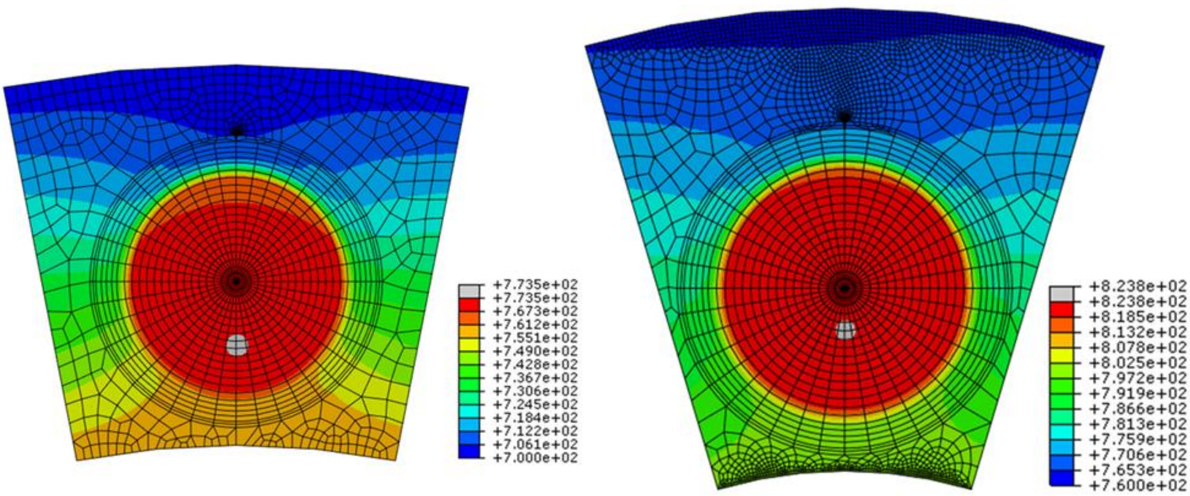

Fig 6. Temperature Field around TRISO Particle
(left: outer pellet position, right : mid pellet position)

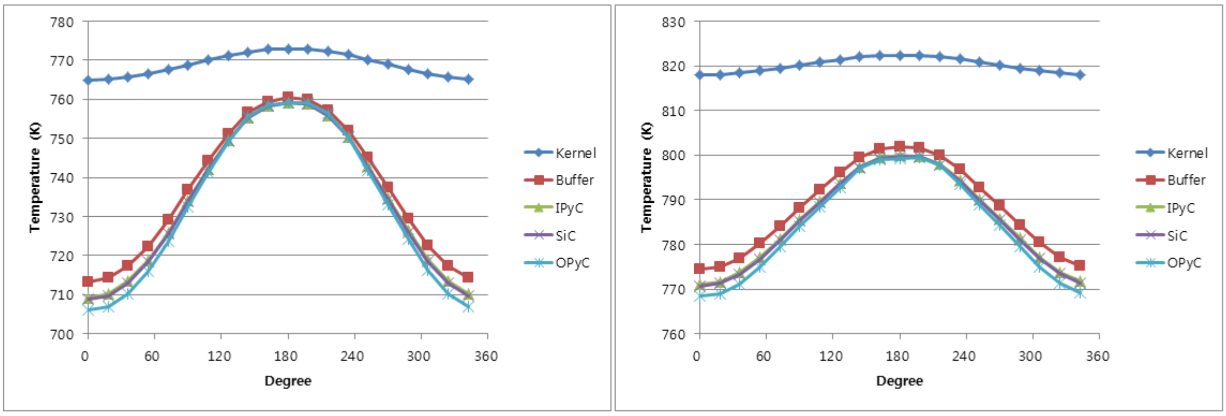

Fig 7. Calculated Boundary Temperature of TRISO Layers
(left: outer pellet position, right : mid pellet position)

4. Conclusions

It has been shown that the radial temperature distribution is symmetric in kernel radius size from 300 to 400 microns for packing fraction of 40%. And temperature distribution become symmetric in axial and radial directions as packing fraction is increased. The temperature increased due to degradation of thermal conductivity of FCM is almost 65K. Also, it has been confirmed that the centerline temperature can be varied depending on the distribution pattern of the particles as a result of distribution patterns. In the temperature analysis of TRISO, the maximum temperature region inside the TRISO particle is shifted to the pellet centerline However, temperature difference between kernel surface and the maximum temperature is small due to high thermal conductivity of kernel.

5. References

[1] K.A. Terrani et al, *Progress on matrix SiC processing and properties for fully ceramic microencapsulated fuel form*, Journal of Nuclear Materials 457 (2015) 9-17

[2] Nicholas R. Brown, *Neutronic evaluation of a PWR with fully ceramic microencapsulated fuel. Part II: Nodal core calculations and preliminary study of thermal hydraulic feedback*, Annals of Nuclear Energy 62 (2013) 548-557

[3] Ji-Han Chun et al, *Safety evaluation of accident-tolerant FCM fueled core with SiC-coated zircalloy cladding for design-basis-accidents and beyond DBAs*, Nuclear Engineering and Design 289 (2015) 287-295