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The Equivalent Cylinder Models for the Homogenization of Pebble Bed Reactor Cores

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1. Introduction

The double heterogeneity in a spherical pebble fuel involved in the homogenization of the pebbles has been one of the main concerns in the analysis of pebble bed reactors. However, many codes do not support a doubly heterogeneous spherical geometry. Therefore, an equivalent 1-D cylindrical cell has been used as an approximation [1]. Recently, Kim et al. proposed the reactivity equivalent physical transform (RPT) method for the treatment of the double heterogeneity [2]. In RPT method, the doubly heterogeneous problem is transformed to an equivalent singly heterogeneous problem. Combining the two methods mentioned above, we can transform the doubly heterogeneous spherical pebble to an equivalent singly heterogeneous cylinder model, which can be solved by popular 2-D codes for singly heterogeneous problems such as HELIOS [3] without any modification of the codes.

In this paper the equivalent cylinder models for the 3-D spherical pebbles were verified using the MC-CARD code [4]. We investigated the effect of the lattice structure and the boundary conditions (BCs) of the cylinder models as well as the effects of some other parameters such as the temperature, enrichment, and fuel to moderator ratio. We also investigated the effect of the burnup by performing a Monte Carlo depletion calculation using the MC-CARD code. The validity of the equivalent cylinder fuel loaded into an infinite slab reactor core was also verified.

2. Methods and Results

2.1 Equivalent Cylinder Model for the Spherical Pebble

The mean chord length of a convex body is given by

$$\bar{l} = 4V/S, \tag{1}$$

where V, S are the volume and the surface area of the body respectively. It is trivial to show that the average chord length is $4R/3$ for a sphere of radius R and $2r$ for an infinite cylinder of radius r.

The fuel radius of the cylinder model can be determined by preserving the chord length of the fuel region. The graphite radius and the boundary of the model can be determined by preserving the volume fractions of each region.

2.2 Verification of the Equivalent Cylinder Model

A spherical pebble with BCC lattice structure was taken as a reference case. The fuel zone radius of the pebble is 2.5cm and the thickness of the graphite shell is 0.5cm. The lattice pitch is 7.1843cm, with which the packing reaction of the pebbles is 0.61. The enrichment of the fuel is 9.6%. The power was assumed to be 0.89kW/pebble. The temperature of the pebble and the helium coolant were assumed to be 800°C and 750°C respectively.

The spherical pebble described above was transformed to three equivalent cylinder models. They are a 1-D cylinder model, 2-D cylinder model with a hexagonal lattice structure, and a 2-D cylinder model with a square lattice structure. In the 1-D cylinder model, the boundary surface of the unit cell was approximated by a cylinder. Two boundary conditions, reflective one and white one, were applied at the boundary of each model.

The equivalent cylinder model should also work even in different conditions from the reference condition. To investigate this, we compared the 3-D spherical pebble model with BCC lattice structure and the 2-D cylinder model with square lattice structure in several different conditions from the reference conditions. In case 1, we lowered the temperature of the pebble and helium gas to a temperature of 27°C. In case 2, we raised the enrichment of the uranium fuel to 19.5%. In case 3, half of the pebbles were replaced with moderator pebbles to simulate the initial pebble bed core.

To verify the accuracy of the equivalent cylinder model during the depletion calculation, we also performed a MC-CARD depletion calculation of the two models.

The validity of the equivalent cylinder fuel loaded in a core should also be verified. Fig. 1 shows the spherical pebble fuels and the equivalent cylinder fuels loaded in a infinite slab reactors with packing fraction of 0.5. Note that the pitches of the cylinders in x- and y- directions were slightly adjusted to space them evenly in x-direction. The power distributions and the effective multiplication factors of two cores from the MC-CARD calculation were compared.

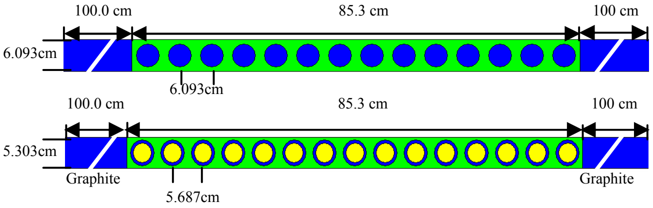

Figure 1. Spherical pebble fuels and the equivalent cylinder fuels loaded in a infinite slab reactor

2.3 Results

Table 1 shows the k_{inf}'s and their standard deviations of the models obtained from the MC-CARD calculation. Except for the 1-D cylinder model with a reflective BC, all the equivalent cylinder models seem to be acceptable. However, 1-D cylinder model with a white BC has relatively large difference. Very small k_{inf} differences are observed for both Case 1 and Case 2 while a relatively large k_{inf} difference is observed in Case 3, in which half of the pebbles are moderator pebbles. The relatively large difference in k_{inf} is ascribed to the fact that we do not preserve the average chord length of the moderator pebble.

Table 1. Comparison of k_{inf} of the spherical and cylinder models

	3-D Sphere	Equivalent Cylinder Model		Error (pcm)
Reference Condition	1.32476 ± 12pcm	1-D RBC	1.33760 ± 12pcm	+1284
		1-D WBC	1.32335 ± 12pcm	-141
		2-D Sq RBC	1.32504 ± 12pcm	+28
		2-D Sq WBC	1.32394 ± 12pcm	-82
		2-D Hex RBC	1.32539 ± 12pcm	+63
		2-D Hex WBC	1.32395 ± 12pcm	-81
Cold State (27°C)	1.42404 ± 12pcm	2-D Sq RBC	1.42461 ± 12pcm	+57
High Enr. (19.5%)	1.39517 ± 12pcm	2-D Sq RBC	1.39539 ± 12pcm	+22
Fuel:Mod (1:1)	1.54304 ± 10pcm	2-D, Sq RBC	1.54140 ± 11pcm	-164

Sq : Square; Hex : Hexagonal; RBC : Reflectice; WBC : White

Figure 2 shows the k_{inf} of the two models during the depletion calculation. At all the burnup points except for only one point, the k_{inf} values of the two models agree with each other to within 2σ. Though the difference of the k_{inf} values is larger than 2σ at a burnup point, value is around 100 pcm, which is very small and still acceptable in neutronics calculation.

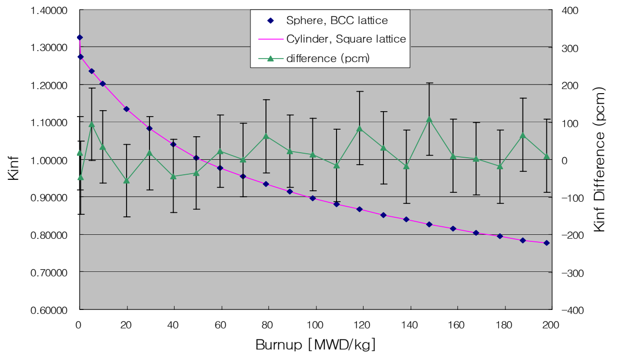

Figure 2. Comparison of k_{inf} of the spherical and cylinder models during the depletion calculation

Figure 3 shows the power distribution of the infinite slab reactor cores loaded with spherical pebble fuels and equivalent cylinder fuels. The power distributions of the two cores are almost identical. The effective multiplication factor of the core loaded with spherical pebble fuels and that of the core loaded with equivalent cylinder fuels are 1.28144 ± 12pcm and 1.27948 ± 12pcm respectively.

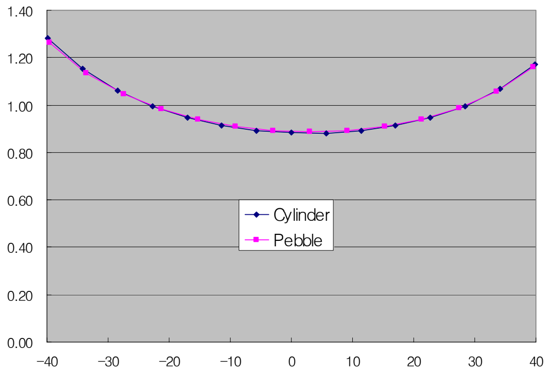

Figure 3. Comparison of power distribution of infinite slab reactor cores loaded with spherical pebble fuels and cylinder fuels

3. Conclusion

In this paper, the validity of the equivalent cylinder models for the 3-D spherical pebbles was verified using the MC-CARD code. We showed that the equivalent cylinder models can be used in place of a 3-D spherical pebble model with an acceptable accuracy. Combining this result with the RPT method, we can transform the doubly heterogeneous spherical pebble into an equivalent singly heterogeneous cylinder model, which can be solved by popular 2-D codes for singly heterogeneous problems such as HELIOS.

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