Physics Calculation on the Homogenization of the Modular Helium Reactor Fuel Particle

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1. Introduction

Compared to the most prevailing commercial reactors like a light water reactor (LWR), the modular helium reactor (MHR) has distinct features from the physics viewpoint such as the use of fuel particles and gas coolant instead of a homogeneous fuel pellet and water coolant, respectively. Though the fuel particle is very small (600-800 μm) and homogeneously dispersed in the graphite matrix, there is a heterogeneity among the fuel particle layers (fuel kernel, porous carbon buffer layer, inner pyrocarbon, silicon carbide and outer pyrocarbon) and between the fuel particle and the compact.

In this study, the homogenization effect was analyzed by the MCNP-4B [Ref. 1] code using "Deep-Burn (DB)" MHR benchmark models developed by General Atomics. [2] The MCNP calculations were performed to obtain the infinite multiplication factors (k_∞) of the heterogeneous and homogeneous models for three cases: a half-size assembly, a triangular geometry with a 1/6 fuel compact and 1/12 coolant, and a unit TRISO particle cell.

2. Physics Calculation

2.1 Half-Size Assembly Model

The k_∞ was estimated for the half-size fuel assembly using 5000 particles/cycle, 20 inactive cycles and 200 active cycles for the MCNP calculation. All the fuel particles, including the fuel kernel and layers, were explicitly described in the heterogeneous model for two different cases: simple cubic (SC) and body-centered cubic (BCC) arrangements. Based on the MCNP results, the effect of the particle arrangement is 0.02%δk, which is comparable to the uncertainty level of the MCNP calculation.

The homogeneous fuel assembly calculation was performed for the SC and BCC arrangement using a mean number density (MND) of the TRISO fuel particle and a fuel compact, and the results are compared to those of the heterogeneous calculations in Table I. For the SC and BCC arrangements of the fuel particles, the k_∞ was under-estimated by 9.3%δk and 9.2%δk, respectively, when the TRISO particle was homogenized with coating layers. If the TRISO particles are homogenized with a fuel compact (graphite matrix), the k_∞ is further reduced by 0.96%δk and 0.90%δk for the SC and BCC arrangement, respectively. Therefore the homogenization of the TRISO fuel particle has a dominant effect on the k_∞ calculation even though the sizes of the fuel kernel and layers are very small. The radial and axial MCNP models are shown in Fig. 1, which includes the driver fuel, transmutation fuel, coolant hole and the graphite block. The driver fuel is made of commercial-grade plutonium and neptunium, while the transmutation fuel is made of americium and curium mixed with burned driver fuel. The radial plot is given for the middle section of the fuel assembly.

Table I. Comparison of the half-size fuel assembly homogeneous calculation

	k_∞	Difference
SC-Heterogeneous	1.02110±0.00077	-
Homogenization of TRISO particle only	0.92845±0.00088	0.09265
Homogenization of TRISO and compact	0.91887±0.00086	0.10223
BCC-Heterogeneous	1.02133±0.00084	-
Homogenization of TRISO particle only	0.92884±0.00080	0.09249
Homogenization of TRISO and compact	0.91986±0.00090	0.10147

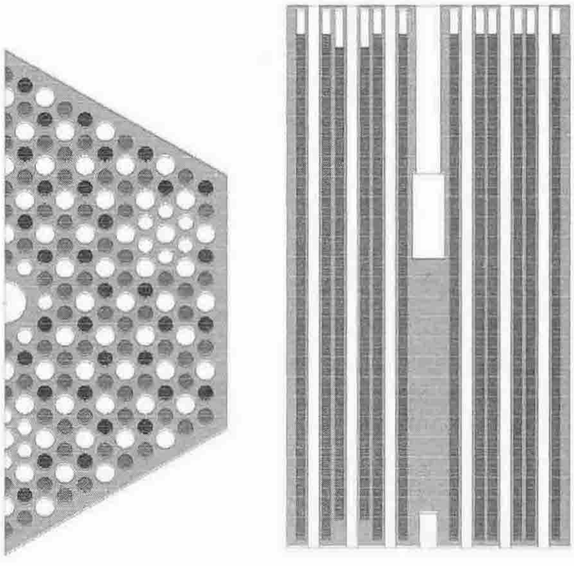

Fig.1 MCNP model of the half-size fuel assembly

2.2 Triangular Lattice Model

In order to reduce the problem size, a hexagonal fuel channel was prepared, consisting of one coolant hole and six 1/3 fuel compacts, which was used for the double-heterogeneous calculations. [3] Considering the symmetry, a triangular lattice was modeled to have a

1/12 coolant hole and a 1/6 fuel compact. This model also showed that the k_∞ is underestimated by 11.1%δk (driver fuel) when the TRISO fuel particle is homogenized with coating layers, which is comparable to the results obtained for the half-size assembly calculation. If the transmutation fuel is used, the underestimation is reduced to 1.6%δk when the TRISO particle is homogenized, which is due to the large subcriticality (0.26705) of the transmutation fuel itself. Therefore this model confirmed that the homogenization of the fuel kernel with coating layers has a dominant effect on the k_∞ calculation.

2.3 TRISO Single Cell Model

Because most of the homogenization effect occurs when the fuel particle is homogenized, a single TRISO particle cell was modeled to observe the detailed physics parameter changes. Table II summarizes the k_∞ values for the driver and transmutation fuels. It can be seen that the homogenization of the driver fuel particle reduces the k_∞ of the single cell by 2.5%δk while that of the transmutation fuel particle reduces the k_∞ value by 0.56%δk. Compared to the cases of the half-size assembly and triangular lattice cell calculations, the underestimation of the k_∞ is smaller for the TRISO single cell calculation because the graphite block is not included in the single cell model, which hardens the neutron spectrum, increases the neutron mean free path and reduces the spatial self-shielding effect.

Table II. Comparison of the TRISO driver single cell calculation

	k_∞	Difference
SC-Heterogeneous	1.18602±0.00063	-
Homogenization of TRISO particle only	1.16088±0.00062	0.02514
Homogenization of TRISO and compact	1.15949±0.00060	0.02653

The calculation also showed that the thermal flux is depressed when the TRISO fuel kernel is homogenized with coating layers, which results in the k_∞ reduction. That is, the diluted fuel particle enhances more interactions of the thermal neutrons with the fuel material and eventually reduces the thermal neutron population in the fuel region.

A comparison of the reaction rates showed that the ^{240}Pu capture reaction increases and the ^{239}Pu fission reaction decreases, which dominates the homogenization effect. For the ^{240}Pu capture reaction, the thermal reaction rate decreases by 32.3%, while the fast reaction rate increases by 4.5% when the fuel kernel is homogenized. As a result, the total capture reaction increases by 3.6%. For the ^{239}Pu fission reaction, it decreases in the thermal energy region by 33.5% and increases in the fast energy region by 1.6%, which results in a total fission reaction rate decrease by 2.1%. The variation of the (n,2n) reaction rate is negligible. For the DB-MHR fuel, therefore, ^{239}Pu and ^{240}Pu have a dominant effect on the k_∞ of the homogenized fuel particle. The results of this study indicate that the TRISO fuel particles should be carefully modeled to produce the reliable physics design parameters which are used for the safety assessment and fuel cycle analyses of the DB-MHR system.

3. Summary and Conclusion

Basic physics of the DB-MHR system were studied, especially for the homogenization of fuel particles. The physics calculation showed that the homogenization of the TRISO fuel kernel with coating layers results in a non-negligible effect on the k_∞ calculation, which is more than 10%δk for the single assembly. Therefore the fuel particles should be carefully modelled in the physics calculation.

Acknowledgements

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References

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