Extension of STREAM Double Heterogeneity Method to Coated TRISO Particles

Hanjoo Kim [a], Sooyoung Choi [a], Deokjung Lee [a*], Hyun Chul Lee [b]
[a] *Ulsan National Institute of Science and Technology (UNIST), 50, UNIST-gil, Ulsan, Korea*
[b] *Korea Atomic Energy Research Institute (KAERI), 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Korea*
**Corresponding author: deokjung@unist.ac.kr*

1. Introduction

The equivalence theory method of the deterministic neutron transport code, STREAM [6], which was designed for High Temperatur Reactor (HTR) doubly heterogenous fuels, has been extended to in order that it can be applied to coated TRISO particles.

As an advanced reactor design, Very High Temperature Reactor (VHTR) adopts a doubly heterogeneous fuel system, in which spherical TRISO fuel particles are randomly dispersed in a graphite matrix of fuel elements, such as fuel compacts or pebbles. The TRISO fuel particles consist of fuel kernels at the center and several coating layers around the fuel kernels. Due to the self-shielding effects of the fuel kernels, the reactivity errors can be as big as several thousands pcm if the materials in the fuel elements are simply homogenized by flux-volume weighting.

In 2015, a new equivalence method for treating doubly heterogeneous TRISO fuel particles was developed by Ulsan National Institute of Science and Technology (UNIST) and Oak Ridge National Laboratory (ORNL) and was implemented in the UNIST in-house lattice physics code, STREAM [1, 2]. However, the method considers the TRISO fuel particles as not having any coating layers, which is a significant limitation for practical application to realistic HTR designs.

A recent study on the Dancoff factor of coated TRISO particles by Ji and Martin [3] analytically derived the Dancoff factor of coated TRISO particles using a dual sphere model.

In this study, the double heterogeneity (DH) equivalence methodology of STREAM was incorporated with Ji's analytical duel sphere Dancoff factor so that the coating layers of practical HTR designs can be modelled with high accuracy without limitations .

2. Methods

In the fuel region of VHTR fuel elements, where coated fuel particles are randomly dispersed in a graphite matrix, the coating layers of the fuel particles can affect Dancoff factor of the system. Thiscauses some bias in reactivity calculations.

2.1 Coating Layer of TRISO Particles

The presence of coating layers in the fuel particles directly affects the chord length of neutrons in the fuel region. The left side of Fig. 1 presents a single sphere model which was implemented in the STREAM code in the previous work, and the right side presents a more practical dual sphere model of coated fuel particles. The most significant difference between the two models is that there is a minimum distance (of two times the layer thickness) between fuel kernels. The gaps between fuel kernels affect the Dancoff factor, *i.e.*, a shadowing effect of neutron escape probability to the graphite matrix in the compact region.

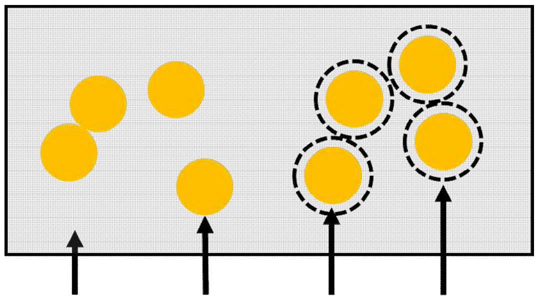

Fig. 1. TRISO fuels with and without coating layers.

2.2 Methodology for DH

An effective cross section of resonance nuclide j for reaction X and group g is expressed as

$$\tilde{\sigma}_{X,g}^{(j)} = \frac{\sigma_0^{(j)} \left\langle \frac{d_f(E)\sigma_X^{(j)}(E)}{d_f(E)\sigma_a^{(j)}(E)+\sigma_0^{(j)}} \frac{\Phi_\infty}{E} \right\rangle}{\sigma_0^{(j)} \left\langle \frac{1}{d_f(E)\sigma_a^{(j)}(E)+\sigma_0^{(j)}} \frac{\Phi_\infty}{E} \right\rangle}, \tag{1}$$

where $\sigma_0^{(j)}$ s background cross section,
$\sigma_a^{(j)}$ absorption cross section,
Φ_∞ asymptotic flux per unit lethargy,
$d_f(E)$ pointwise disadvantage factor in fuel,
$\tilde{\sigma}$ the tilde means homogenized quantity withina compact region,
$\langle\ \rangle$ brackets represents integration over an energy group.

The disadvantage factor can be written as

$$d_f(E) = \frac{1}{1+\omega\sigma_a^{(j)}(E)} , \quad (2)$$

and

$$\omega = \frac{v_m(1-\beta)}{v_c\sigma_b^{(j)}} , \quad (3)$$

where β is the heterogeneity parameter; which is defined as

$$\beta = \frac{1-c}{\overline{l}_m\Sigma_m} . \quad (4)$$

and where

$\sigma_b^{(j)}$ background cross section,

v_c $= v_f + v_m$,

v_f, v_m fuel (moderator) volume fraction in compact region,

c Dancoff factor of the kernel,

$\overline{l}_m$ mean chord length of moderator,

and

Σ_m Total cross section of moderator region.

The Dancoff factor of an infinite array of fuel kernels with a coating layer can be written as

$$c = \frac{1}{(\overline{\ell}_m-\tau)\bullet\Sigma^*}e^{\left(-\frac{\tau}{\lambda_m}\right)} , \quad (5)$$

and the effective cross section is

$$\Sigma^* = \frac{1}{\lambda_m} + \frac{1}{\overline{\ell}_m-\tau} , \quad (6)$$

where

λ_m mean free path in the moderator,

τ minimum distance between fuel kernel.

Details of the DH self-shielding method methodology can be found in references 1 and 2, and the Dancoff factor in reference 3 .

3. Verifications

3.1 Model Description

Simple pin cell problems are used for verification of the methodology. To increase practicality, TRISO particles with a fuel volume fraction of 9.33% coated with two PyC layers and one SiC layer [4] are firstly introduced to the fuel compact region, and layers are homogenized with a graphite moderator outside the fuel kernel, resulting in a moderator composition with 0.102g/cm^3 of Si and 1.612g/cm^3 of graphite. In Monte Carlo modeling, a hypothetical layer composed of the same material as the matrix outside the fuel kernel is implemented the outside of the kernel to simulate the minimum distance between fuel kernels. The configuration of the fuel pin with the graphite moderator is as shown in Fig. 2. The density of materials in each region are 1.75 g/cm^3 for the graphite moderator, 7.55×10^{-5} g/cm^3 for He coolant, and in the fuel compact region, each UO_2 fuel kernel has a desity of 10.41 g/cm^3 of density.

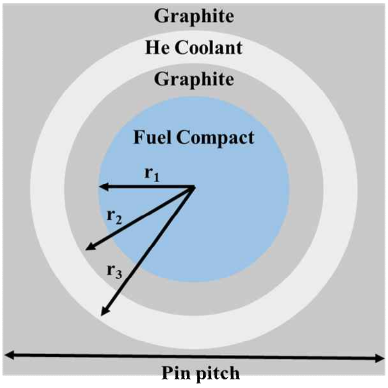

Fig. 2. Configuration of fuel pin.

Table I: Pin geometry (Unit: cm)

r_1	1.2000
r_2	1.6250
r_3	2.0500
Pin pitch	4.7926

3.2 Case Description and Results

The DH effect is mainly affected by fuel kernel size and fuel fraction in the compact region. Several cases with various conditions of the fuel region are calculated with both a deterministic code, STREAM, and a reference Monte Carlo code, McCARD, [5].

As shown in Table II and III, 43 cases are composed of various fuel compact conditions. Fuel volume fraction is from 4.3% to 10.42%, fuel kernel radius is from 250μm to 400 μm. The thickness of coating layer varies from 0 μm to 250 μm. In the SH (single heterogeneity), the compact region is homogenized. The temperature used for verification is 300 K. The verification of the method is focused on the double heterogeneity effect; the difference between the k_{eff} of the DH case and that of the SH case.

Table II: Description of case 1-23

Case Number	Fuel Enrichment [w/o]	Kernel Radius [cm]	Fuel Fraction [%]	Layer Thickness [cm]
1	3	0.025	4.30	SH
2				0.000
3				0.003
4				0.013
5				0.017
6				0.023
7			8.60	SH
8				0.000
9				0.003
10				0.013
11				0.017
12		0.04	4.30	SH
13				0.000
14				0.003
15				0.013
16				0.017
17				0.023
18			8.60	SH
19				0.000
20				0.003
21				0.013
22				0.017
23				0.023

Table III: Description of case 24-43

Case Number	Fuel Enrichment [w/o]	Kernel Radius [cm]	Fuel Fraction [%]	Layer Thick [cm]
24	6	0.025	6.25	SH
25				0.000
26				0.005
27				0.015
28				0.025
29			10.42	SH
30				0.000
31				0.005
32				0.010
33				0.015
34		0.035	6.25	SH
35				0.000
36				0.005
37				0.015
38				0.025
39			10.42	SH
40				0.000
41				0.005
42				0.010
43				0.015

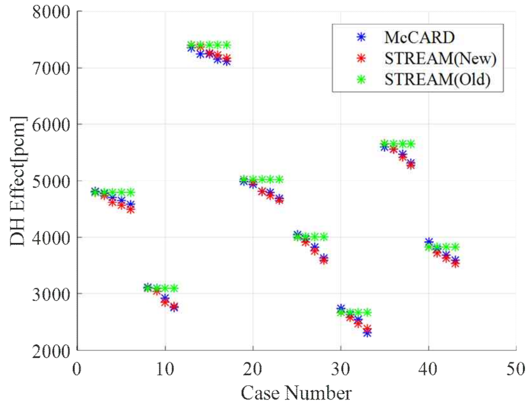

Fig. 3. DH Effects.

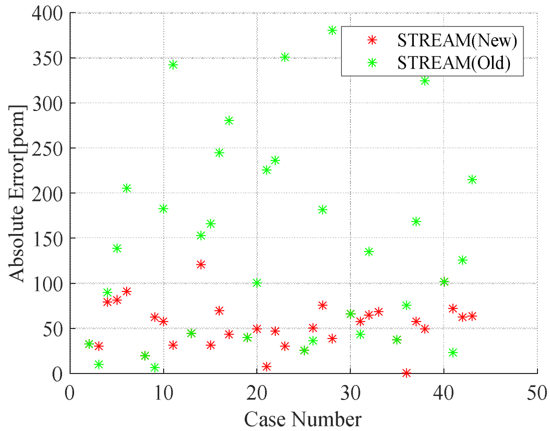

Fig. 4. Errors of DH effect.

The DH effects are shown in Fig. 3. The DH effect decreases as the thickness of the coating layer increases because spatial self-shielding decreases with increases in the coating layer. STREAM closely follows the layer effect of coated TRISO particles using the modified method for treating double heterogeneity. Fig. 4. Shows the errors in the STREAM results alongside those of previous and current methods. This comparison highlights the advantages of the current method, errors of the old STREAM varying up to 400 pcm while those of new method being mostly within 100 pcm.

4. Conclusions

The analytically derived Dancoff factor, which considers the distance between fuel particles of TRISO fuels, was incorporated into the DH method of the UNIST inhouse neutron transport code STREAM for treating the self-shielding effect of doubly heterogeneous fuel elements. The verification cases demonstrate that the modified equivalence method can successfully overcome the limit of the previous method of modelling the coating layer of TRISO particle.

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