Reactivity-Equivalent Physical Transformation for Homogenization of Double-Heterogeneous Fuels

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1. Introduction

In VHTRs, a particulate fuel with multi-coating layers, which is called TRISO, is employed to achieve a high fuel performance. The TRISO fuels are utilized in two fuel types, either a cylindrical compact or a spherical pebble. In both fuel types, TRISO particles are randomly dispersed in a graphite matrix with a relatively low volume fraction. This special fuel configuration leads to the so-called double-heterogeneity problem, which requires special computational methodology. Currently, most conventional lattice codes cannot handle the double-heterogeneity media and only a few computer code systems such as DRAGON[1] are applicable to the problem, with a limited accuracy. Furthermore, a full-scale application of the Monte Carlo method to the double-heterogeneous problem is also very challenging due to the huge number of TRISO fuels randomly distributed.

In this paper, a novel method is proposed to eliminate the double-heterogeneity, which makes the conventional lattice codes applicable to the VHTR fuel elements.

2. The RPT Methodology

In order to use the conventional lattice code systems for the VHTR fuels, the double-heterogeneous region needs to be converted to a homogeneous one. It is known that a simple volume-weighted homogenization (VWH) of a double-heterogeneous fuel zone results in a highly under-estimated reactivity. This is mainly because the resonance self-shielding of the fuel is substantially reduced in the homogeneous case.

In the RPT method, the self-shielding effect of fuel is adjusted by modifying the physical configuration of the problem. The concept of the RPT method is depicted in Fig. 1 for a cylindrical and spherical geometry: first, the fuel particles are moved into a smaller volume and then the inner double-heterogeneous fuel zone is simply homogenized in a volume-weighted sense. In the RPT method, the reduced radius (r_{rpt}) of the new homogeneous fuel zone is determined such that the resulting neutron multiplication factor should be equal to the reference one. It is worthwhile to note that reducing the fuel radius increases the reactivity since the self-shielding effect of the fuel is enhanced. The reference solution can be obtained by either a high-fidelity deterministic code or a Monte Carlo method.

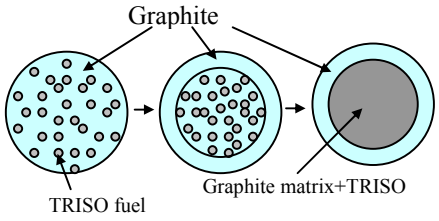

Fig. 1. The RPT concept.

3. Application Double-Heterogeneous Fuels

The RPT method has been applied to a prismatic fuel assembly of the US NGNP design study.[2] The UO_2 kernel diameter of the TRISO is 350μm and coating thicknesses are as follows: buffer=100μm, inner PyC=35μm, SiC=35μm, outer PyC=40μm. The fuel packing fraction is 29% and the uranium enrichment is 10wt%. The radius of the fuel compact is 0.6225cm. All neutronic calculations were performed with the DRAGON code.

Table I. Effects of the RPT method on the four factors

Method (r_f=0.6225cm)	Four factors			
	η	*f*	*p*	ε
No burnable absorber				
Reference	2.07779	0.99218	0.70450	1.00075
VWH	2.08576 (0.38%)	0.99225 (0.01%)	0.66539 (-5.55%)	1.00066 (-0.01%)
RPT (r_{rpt}=0.3841cm)	2.07776 (0.00%)	0.99217 (0.00%)	0.70453 (0.00%)	1.00075 (0.00%)
With B_4C burnable absorber				
Reference	2.13095	0.73828	0.69633	1.00075
VWH	2.14117 (0.48%)	0.73982 (0.21%)	0.65766 (-5.55%)	1.00061 (-0.01%)
RPT (r_{rpt}=0.3830cm)	2.13085 (-0.01%)	0.73807 (-0.03%)	0.69659 (-0.04%)	1.00075 (0.00%)

Table I compares the RPT and VWH methods in terms of the four factors for two types of fuel assemblies, one without a burnable absorber (BA) and the other one with a B_4C BA. One can note that the large error of VWH is mainly ascribed to a substantially smaller resonance escape probability. However, it is clearly observed that the RPT method provides almost identical four factors. This is because the self-shielding phenomenon is enhanced by reducing the fuel radius. The corrected self-shielding effects also leads to a more accurate neutron spectrum, thereby correcting other factors such as η, *f,*

and ε. It is also noteworthy that the RPT radius is very similar for the two significantly different fuel assemblies and it is much smaller than the original radius of the fuel compact.

Once the RPT radius is determined for an initial condition of a fuel assembly, all the other calculations can be done with the conventional methodologies. In Figs. 2 and 3, accuracy of the RPT method is assessed during the assembly depletion for the two fuel assemblies. It is clearly observed that the RPT solution matched very well up to a very high burnup of 198 GWD/tU for the two cases, while the VWH solution has a large error. With respect to the assembly power distribution, the RPT method has a negligible error.

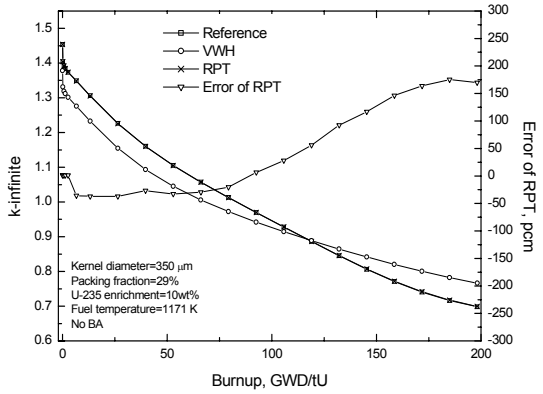

Fig. 2. Accuracy of RPT during burnup (no BA).

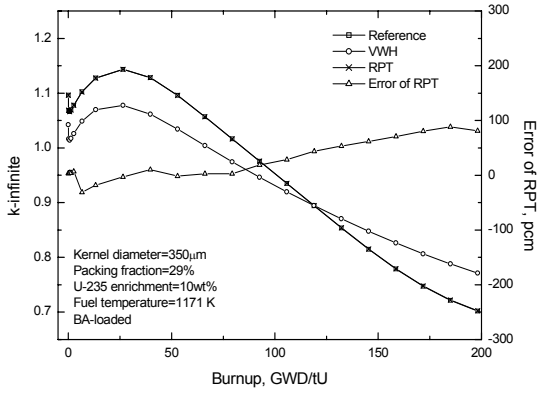

Fig. 3. Accuracy of RPT during burnup (BA-loaded).

Next, the RPT method was applied to a pebble fuel with a 6cm diameter. In this case, the calculations were done with the MCCARD Monte Carlo code. A simple cubic arrangement of pebbles was assumed and a UO_2 fuel kernel of 10wt.% enrichment was used. In an actual pebble, about 15,000 TRISOs are embedded in a pebble, which cannot be treated with the MCCARD code due to the memory requirement and computing time. Instead, 1,000 TRISO particles with a kernel diameter of 1230μm are explicitly modeled here. Due to the large kernel, the double-heterogeneity is huge, 11,418 pcm. Nevertheless, the RPT show a good agreement as shown in Fig. 4. The RPT performance would be much better for the actual pebble with a substantially smaller double-heterogeneity.

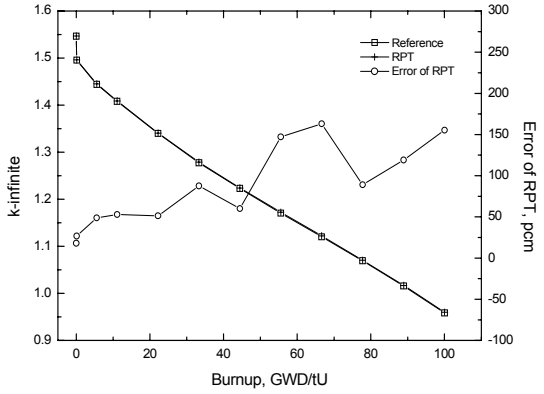

Fig. 4. Burnup with RPT for a pebble fuel.

4. Conclusions

With the aid of the RPT method, the VHTR fuels with a double-heterogeneity can be very efficiently and accurately analyzed by the conventional lattice code systems. An important advantage of the RPT approach is that the reference solution can be obtained by using the Monte Carlo method instead of approximate deterministic codes. Also, the possible errors caused by the randomness of the particle distribution can easily be taken into account when determining the RPT parameter. A synergetic combination of the deterministic and Monte Carlo methods is possible with the RPT approach.

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