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Depletion benchmarks calculation of random media using explicit modeling approach of RMC

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ABSTRACT

Monte Carlo method plays an important role in accurate simulation of random media, owing to its advantages of the flexible geometry modeling and the use of continuous-energy nuclear cross sections. Three stochastic geometry modeling methods including Random Lattice Method, Chord Length Sampling and explicit modeling approach with mesh acceleration technique, have been implemented in RMC to simulate the particle transport in the dispersed fuels, in which the explicit modeling method is regarded as the best choice. In this paper, the explicit modeling method is applied to the depletion benchmark for HTGR fuel element, and the method of combination of adjacent burnup regions has been proposed and investigated. The results show that the explicit modeling can provide detailed burnup distribution of individual TRISO particles, and this work would serve as a supplement for the HTGR fuel depletion benchmark calculations. The combination of adjacent burnup regions can effectively reduce the memory footprint while keeping the computational accuracy.

1. Introduction

The particle transport in random media has many applications, such as in the designs and analysis of Very High Temperature Gas-Cooled Reactors (VHTRs), light water reactors (LWRs) with Fully Ceramic Microencapsulated (FCM) fuel and some experimental research reactors.

Many efforts have been made for the deterministic methods to deal with the transport and burnup problems of random media (Sanchez, 2004; Grimod et al., 2015), delivering space-dependent results using fuel multi-types and also using several depletion layers per fuel particle. In these deterministic methods, homogenization approach must be made to deal with stochastic heterogeneity. Special treatment for self-shielding is also needed as the stochastic media has strong effect of spatial and energy self-shielding.

In order to deal with the random microscopic particles, three stochastic geometry modeling methods have been implemented in RMC code, which are Random Lattice Method, Chord Length Sampling and explicit modeling approach with mesh acceleration technique (Liu et al., 2015a, 2015b). RMC is a continuous-energy Reactor Monte Carlo neutron and photon transport code being developed by Department of Engineering Physics at Tsinghua University, Beijing (Wang et al., 2014). RMC has been successfully applied to the modeling and transport calculation of random media such as the double-heterogeneous pebble-bed reactors (She et al., 2015). This paper will present new method and results of burnup calculation of random media with RMC.

A HTGR fuel element depletion benchmark (DeHart and Ulses, 2009) was proposed to compare different methodologies and codes used for modeling HTGR fuel. This depletion benchmark consists of three cases: (I) an infinite lattice of TRISO fuel particles, (II) an infinite lattice of fuel pebbles, and (III) a prismatic super-cell including fuel and coolant channels. In previous studies (Leppänen and DeHart, 2009; DeHart et al., 2009; Fridman and Shwageraus, 2010), several participants have provided numerical results calculated from both deterministic and Monte Carlo (MC) codes. In those MC models, the TRISO particles were usually modeled as regular lattice, and/or, depleted as a single material.

By using the high-fidelity explicit modeling method, this paper presents some new results for benchmark case II and III, which would serve as a supplement for the HTGR fuel depletion benchmark calculations.

Furthermore, when dealing with the burnup simulation of full-core scale, the problem of memory footprint is inescapable as the burnup calculations are carried on for ten millions or a hundred millions random distributed fuel particles. If each TRISO particle is regarded as an individual burnup region, the memory footprint would be unacceptable. To cope with this problem, the reactivity

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equivalent physical transformation (RPT) method (Kim and Baek, 2005) was adopted to convert the heterogeneous fuel particles in the fuel compact into a conventional homogenized fuel. Moreover, a method to conduct burnup tallies merging arbitrary regions to reduce required memories for the VHTR burnup analysis was suggested by McCARD group (Lee et al., 2010). In this method, the merging is performed in the fuel compacts or pins level, so the fuel compacts or pins are not depleted explicitly. In this paper, the method of combination of adjacent burnup regions has been proposed and investigated.

The remainder of this paper is organized as follows. Section 2 introduces the computational method of explicit modeling with mesh acceleration and burnup calculation of RMC. The results and analysis of HTGR fuel element depletion benchmark are given in Section 3. The method of combination of adjacent burnup regions is proposed and investigated in Section 4. The conclusions are presented in Section 5.

2. Computational method

2.1. Explicit modeling with mesh acceleration

The stochastic geometry modeling of RMC is based on ray tracking process, and applied to three dimensional continuous-energy Monte Carlo simulations. A new dispersed-sphere lattice has been developed in RMC. The spheres can be filled by universes with detailed structures such as multi-level spheres or sub-level dispersed-sphere lattice for double-heterogeneous reactors.

The mesh acceleration technique uses the virtual meshes which divide the domain of dispersed-sphere lattice to locate the positions of fuel particles. The mesh acceleration technique is used for both the generation of distributions of fuel particles or pebbles, and the geometry tracking process, as show in Fig. 1.

In the geometry tracking process, the traditional ray tracking has to calculate the distances to all the surfaces of fuel particles to determine which one the neutron will advance to. While with the mesh acceleration technique, the meshes can help to locate the fuel particles in the flight path. In this way, the time cost of the geometry tracking can greatly reduce.

The explicit modeling of RMC can handle poly-size and poly-component fuel particles. This approach can be applied to several levels modeling, for example, pebbles in the core and particles inside a pebble. The explicit modeling approach with mesh acceleration technique has been successfully applied to the modeling and calculation of the double-heterogeneous pebble-bed reactors (She et al., 2015). The power distributions, burnup calculations and geometry plotting are also available in the explicit modeling of stochastic geometry. Therefore, the explicit modeling method is applied to the study of burnup calculation of random media.

2.2. Burnup calculation of RMC

RMC is developed with an embedded depletion module aimed at performing burnup calculations of large-scale problems with high efficiency. Several measures have been taken to strengthen the burnup capabilities of RMC.

- A new depletion module called DEPTH is developed and implemented. The DEPTH module is able to handle detailed depletion chains containing thousands of isotopes at an extremely fast speed with accuracy owing to its advanced matrix-exponential solvers including the rational approximation methods and the Laguerre polynomial approximation method. Numerical results of several depletion cases have shown that the DEPTH module is more accurate and efficient than the formerly embedded depletion module (She et al., 2013).
- The Energy-Bin method and the Cell-Mapping method are implemented to speed up the transport calculations with large numbers of nuclides and tally cells (She et al., 2013).
- Auto expansion of burnable cells and materials in lattice structure (She et al., 2013).
- The batch tally method and the parallelized depletion module have been utilized to better handle cases with massive amounts of burnup regions in parallel calculations (She et al., 2013).

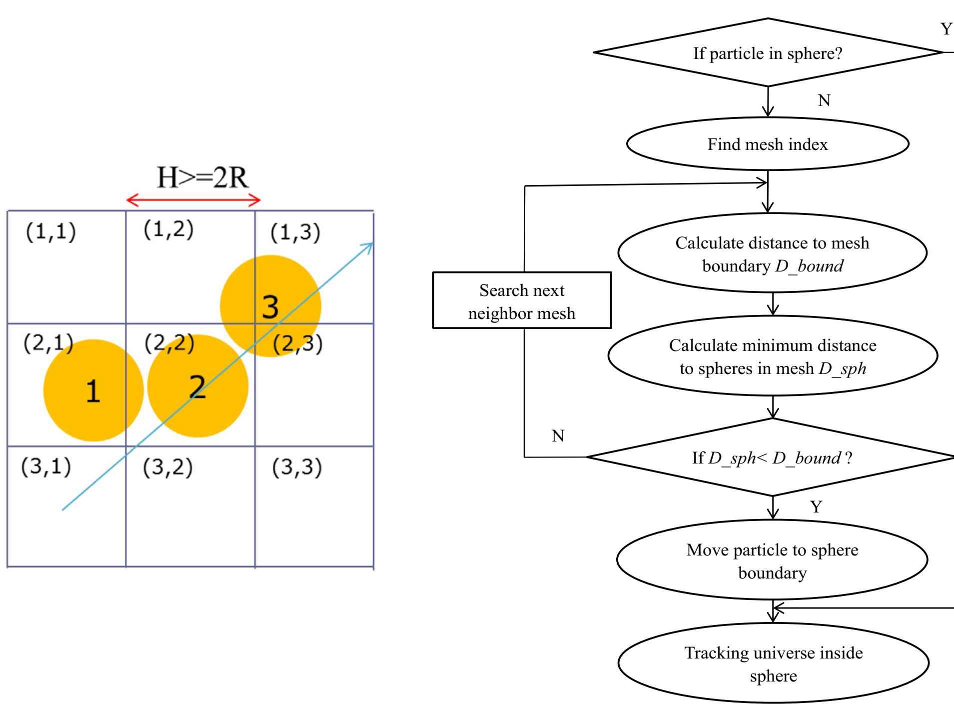

Fig. 1. Ray tracking with mesh acceleration.