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Random geometry capability in RMC code for explicit analysis of polytype particle/pebble and applications to HTR-10 benchmark

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ABSTRACT

With the increasing demands of high fidelity neutronics analysis and the development of computer technology, Monte Carlo method is becoming more and more attractive in accurate simulation of pebble bed High Temperature gas-cooled Reactor (HTR), owing to its advantages of the flexible geometry modeling and the use of continuous-energy nuclear cross sections. For the double-heterogeneous geometry of pebble bed, traditional Monte Carlo codes can treat it by explicit geometry description. However, packing methods such as Random Sequential Addition (RSA) can only produce a sphere packing up to 38% volume packing fraction, while Discrete Element Method (DEM) is troublesome and also time consuming. Moreover, traditional Monte Carlo codes are difficult and inconvenient to simulate the mixed and polytype particles or pebbles. A new random geometry method was developed in Monte Carlo code RMC to simulate the particle transport in polytype particle/pebble in double heterogeneous geometry systems. This method was verified by some test cases, and applied to the full core calculations of HTR-10 benchmark. The reactivity, temperature coefficient and control rod worth of HTR-10 were compared for full core and initial core in helium and air atmosphere respectively, and the results agree well with the benchmark results and experimental results. This work would provide an efficient tool for the innovative design of pebble bed, prism HTRs and molten salt reactors with polytype particles or pebbles using Monte Carlo method.

1. Introduction

Monte Carlo method plays an important role in accurate simulation of High Temperature Gas-Cooled Reactors (HTR), owing to its advantages of the flexible geometry modeling and the use of continuous-energy nuclear cross sections. Recently, the Pebble Bed Fluoride salt cooled High temperature Reactor (PB-FHR) has also been proposed (Fratoni and Greenspan, 2011), which is an innovative reactor that combines the advantages of Molten Salt Reactor (MSR) and HTGR. PB-FHR adopts the similar fuel pebbles of PB-HTGR but with FLiBe salt as coolant. For the innovative design of pebble bed, prism HTRs and molten salt reactors, there may be more than one kind of particles or pebbles in the system, such as the fuel particles with different enrichments, burnable poison particles, graphite pebbles or fuel pebbles with different enrichments.

Different treatments have been used to deal with the heterogeneous or double-heterogeneous geometry of these reactors. In some researches, the particle distributions in stochastic media are assumed the regular lattice, while in the others, the explicit packing methods such as Random Sequential Addition (RSA) (Widom, 1966) and Discrete Element Method (DEM) (Ougouag et al., 2005) are used, by generating the random coordinates of the particles/pebbles. However, traditional geometry with repeated structure has difficulties in explicit modeling polytype particle/pebble, due to the arbitrary packing fractions of different kinds of particles or pebbles. Although, packing methods such as Random Sequential Addition (RSA) and Discrete Element Method (DEM) could solve the polytype particle/pebble problems to some extent, but these methods are troublesome in geometry modeling and time consuming.

In this paper, a new Random Universe Geometry method was developed and implemented in Monte Carlo code RMC, for explicit analysis of polytype particle/pebble in double heterogeneous geometry systems, such as HTRs and molten salt reactors. This method was verified by some constructed mixed particles/pebbles

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problems and also simplified HTR-10 full core problem to test the feasibility, and the results show that the random geometry modeling can provide explicit packing fraction of different kinds of particles or pebbles. The results are also compared with that calculated by RSA method and regular structure, and agree quite well. At last, the method was applied to the full core calculations of HTR-10 benchmark. The reactivity, temperature coefficient and control rod worth of HTR-10 were compared for full core and initial core both in helium and air atmosphere, and the results agree well with the benchmark results. This work would provide an effective tool for the innovative design of pebble bed, prism HTRs and molten salt reactors with polytype particles or pebbles using Monte Carlo method.

The remainder of this paper is organized as follows. Section 2 introduces the methodology, including explicit modeling approach with RSA and the proposed random universe geometry method. In Section 3, the proposed method was verified by some constructed mixed particles/pebbles problems and also simplified HTR-10 full core problem. In Section 4, the proposed method was applied to the full core calculations of HTR-10 benchmark. Finally, the conclusions are presented in Section 5.

2. Computational methods

2.1. Explicit modeling approach with RSA

RMC (Wang et al., 2015) is a continuous-energy Reactor Monte Carlo neutron and photon transport code being developed by Department of Engineering Physics at Tsinghua University, Beijing. RMC adopts constructive solid geometry technique represented by surfaces, cells, universes and lattices for flexible geometry modeling. The ray-tracking method is employed as main option for particle transport.

Different from the Random Lattice Method in MCNP5 (Brown and Martin, 2004) and Chord Length Sampling in MVP (Murata et al., 1997) and SERPENT (Leppänen, 2007), which use the approximations for realizing the random geometry, the explicit modeling approach generates the coordinates of fuel particles or pebbles by RSA and treats them explicitly, without any approximations.

Besides the current regular cubic and hexagonal lattices in RMC, a new dispersed-sphere lattice has been developed to describe the stochastic media in which huge number of spheres are distributed randomly in the matrices. 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 (Liu et al., 2015, 2016) is used for both the generation of distributions of fuel particles or pebbles, and the geometry tracking process. The mesh acceleration technique uses the virtual meshes which divide the domain of dispersed-sphere lattice to locate the positions of fuel particles, as shown in Fig. 1.

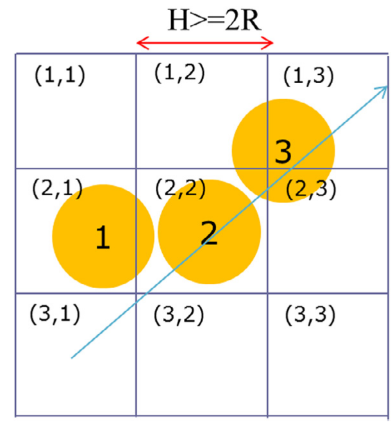

Fig. 1. Explicit modeling approach with mesh acceleration.

2.2. Random universe geometry method

The explicit modeling approach with mesh acceleration has high accuracy and efficacy. However, explicit modeling approach must generate a lots of different realizations and take the average. Moreover, RSA can only produce a sphere packing up to 38% volume packing fraction (Ji et al., 2014). For particles in Fully Ceramic Microencapsulated (FCM) fuel in PWR or fuel pebble in pebble bed HTRs, the packing fractions are larger than 38%. RSA is not valid in these cases, while Discrete Element Method (DEM) are troublesome and time consuming.

There a new Random Universe Geometry method was introduced, as shown in Fig. 2. Given the number ratio of fuel pebble to graphite pebble is 5–4, a single realization was shown on the left of Fig. 2. The nine pebbles are randomly assigned to be fuel or graphite based on the number ratio. However, the random assignment in Fig. 2 (left) is just one case of the realizations. Generally, explicit modeling approach such as RSA must generate a lots of different realizations and take the average.

For the new Random Universe Geometry method, each time a particle encounters a cell filled by universe flagged as stochastic, a random sampling will be performed to decide which universe with detailed geometry the neutron will advance to. For example, the yellow one is fuel with 5/9 probability to be sampled, while the green one is graphite with 4/9 probability. In this way, the random assignment is performed during the neutron transport. The RUG method can achieve the mean value by simulating only one time.

A typical case is the different types of particles or pebbles have the same radius which are mixed in the matrix or container. For example, the graphite pebbles and fuel pebbles in HTR. Let's assume that there are N_1 yellow particles and N_2 green particles. If the lattices are cubes, then the total volume of the container is

$$\mathrm{V}_{tot} = (\mathrm{N}_1 + \mathrm{N}_2) * \mathrm{L}^3 \tag{1}$$

The volume fraction of yellow particles is

$$\mathrm{VF}_1 = \frac{N_1 * V_{particle}}{(N_1 + N_2) * L^3} = \frac{N_1}{N_1 + N_2} * \frac{V_{particle}}{L^3} = \frac{N_1}{N_1 + N_2} * PF_1 \tag{2}$$

where and $V_{particle}$ is the volume of a particle, PF_1 is the packing fraction of yellow particle in each lattice. Therefore, the probabilities A and B follow:

$$A/B = \mathrm{VF}_1/\mathrm{VF}_2 = N_1/N_2 \tag{3}$$

Different types of particles can be sampled based on the probabilities in Eq. (3). It can be found that the pitch is the same for yellow one and green one. In this way, different kinds of particles or pebbles can be mixed by different packing fractions.

As the Random Universe Geometry (RUG) method is based on the traditional regular lattice in repeated structure, the highest packing fraction of RUG method is the same as the traditional regular lattice. Therefore, the highest packing fraction of RUG method is determined by the regular lattice used in calculation, for example, if the center hexagonal prism lattice is used in the calculation, the theoretical highest packing fraction could be around 61%.

Another special treatment has to be considered. In the power iteration of Monte Carlo simulation, the source neutrons of $i+1$th generation were born in the same fission site of the fission neutrons in the i^{th} generation, as shown in Fig. 3. Therefore, when sampling the source neutrons of the new generation, the source neutrons must be always located in the fuel. In this way, the uni-