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Neutronic simulation of a pebble bed reactor considering its double heterogeneous nature

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HIGHLIGHTS

- A new model is successfully developed for a pebble bed reactor simulation.
- In the model, the double heterogeneous nature is considered using MCNP5 code.
- The initial and full core criticality, control rod worth, *etc.* are calculated to validate it.
- Results confirm the capability of Monte Carlo codes in modeling complex geometries.

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ABSTRACT

In pebble bed reactors, the core is filled with thousands of graphite and fuel pebbles. Fuel pebbles in these reactors consist of TRISO particles, which are embedded in a graphite matrix stochastically. The reactor core is also stochastically filled with pebbles. These two stochastic geometries comprise the so-called double heterogeneous nature of this type of reactor. In this paper, a pebble bed reactor, the HTR-10, is used to demonstrate a treatment of this double heterogeneity using the MCNP5 Monte Carlo code and MATLAB programming. In this technique, TRISO particles are modeled in a pebble using the expanded FILL and LATTICE features of MCNP5. MATLAB is used to generate random numbers which represent the location of pebbles in the core. Centers of pebbles are generated stochastically and uniformly and then transferred into the MCNP5 input file as the centers of spherical surfaces. In this model, there is no approximation to the actual geometry. In other words, the double heterogeneous nature is preserved while truncating neither the pebbles in the core nor the particles in the pebble matrix. Finally, to validate the model, benchmark problems of IAEA are used. Very good agreement with experimental results is observed.

1. Introduction

Nowadays, the operating nuclear power reactors are generally of generation II or III nuclear reactor designs. However the modern reactors, the so-called Generation IV nuclear reactors, are currently being developed. The ability to provide sustainable energy generation, maintain a high economic gain and operational efficiency, utilize effective fuel utilization and minimize waste, demonstrate passive safety and proliferation resistance, *etc.* are the goals of Generation IV nuclear reactors. The Very-High Temperature Reactor (VHTR) design is one of the six candidates for this generation. The VHTR is a graphite-moderated, helium-cooled reactor. The core geometry of the VHTR design can be either a prismatic block core such as the operating Japanese High-Temperature Test Reactor (HTTR), or a pebble-bed core such as the Chinese High-Temperature Reactor 10 (HTR-10) (US DOE, 2002). In VHTR design, the large negative temperature coefficient of reactivity and the large heat capacity of its core structure prevent the fuel from exceeding failure temperatures (Hu et al., 2004, 2006). Multi-barriers prevent the release of fission products from the fuel matrix, *i.e.*, the fuel kernel, the coatings, the graphite matrix, the primary circuit and the reactor containment provide defense-in-depth. This inherent safety eliminates the need for active safety systems.

In pebble bed reactors, the core is filled with thousands of fuel pebbles. Each containing about thousands of TRISO (TRIstructural ISOtropic) coated fuel particles embedded within the fuel zone. Some reactors, such as the HTR-10, also contain graphite pebbles which moderate the reaction but are not fueled. Pebble bed reactors also have features that distinguish them from the prismatic HTGRs, *e.g.*, low excess reactivity because of its on-line refueling

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Table 1
Deviations in the benchmark definition (IAEA, 2003).

Parameters	Original	Revised (as built)	Relative changes[a] (%)
Density of dummy pebbles (g/cm3)	1.73	1.84	5.9783
Boron equivalent of impurities in dummy pebbles (ppm)	1.3	0.125	940
Core atmosphere at initial criticality	Helium	Air	–

[a] $\frac{revised-orignal}{revised} \times 100$.

and high heat transfer due to a high surface-to-volume ratio of both the TRISO coated fuel particles and fuel pebbles (Bende, 1999). At startup, the HTR-10 reactor core is stochastically filled with fuel and dummy pebbles a ratio of 57:43. For accurate neutronics analysis of pebble bed reactor core, unique phenomena like non-uniform packing density, neutron streaming between pebbles and variations in Dancoff factor may lead to unacceptable errors if not treated properly (Abedi et al., 2011; Auwerda et al., 2010).

The HTR-10 reactor is usually used for validation of neutronics tools as it is the only pebble bed reactor currently in operation. This reactor is built and operated by the Institute of Nuclear Energy and Technology (INET), Tsinghua University, Beijing, China. The HTR-10 reached its first criticality in December 2000 and reached its rated power in January 2003. Some HTR-10 benchmark problems with focus on its core physics calculations are performed using both diffusion and Monte Carlo codes before its first criticality (IAEA, 2003). Critically analyses of pebble bed reactors have also been performed (Bakhshayesh and Vosoughi, 2009; Seker and Çolak, 2003; Karriem et al., 2000; Zibi et al., 2010). In these early studies, however, the effects of double heterogeneity are not fully considered although truncated TRISO particles in fuel pebbles and truncated pebbles in the core are eliminated. Later, Çolak and Seker (2005) inserted only fuel pebbles with stochastic TRISO particles into their previous model. Kim et al. (2011) simulated a random geometry configuration of the pebble type core by employing a Body Centered Cubic (BCC) crystal (not random) structure as a lattice cell and eliminating truncated TRISO particles and pebbles. Simultaneously, another new model was developed by Abedi et al. (2011) in which the fuel and dummy pebbles are distributed randomly in a regular crystal structure using Simple Cubic (SC) and Simple Hexagonal (SH) structures. In this model, not only the stochastic distribution of TRISO particles in the fuel pebbles is treated but truncated TRISO particles and pebbles are also eliminated.

However, the experimental packing fraction (PF), *i.e.*, 0.61 is not achievable using regular crystal structures like BCC, SH, SC, *etc*. The packing fraction of these structures is about 0.68, 0.605 and 0.52, respectively. It is recognized that the effective neutron multiplication factor (k_{eff}) calculations are highly sensitive to the core packing fraction (Abedi et al., 2011). To reduce the packing fraction of structures with greater magnitude than experimental state, some pebbles are eliminated or the core is modeled using non-tangent pebbles. Furthermore, in these structures, the core height is a multiple of a pebble diameter or a defined lattice cell height. Therefore, linear interpolation is usually used to obtain the critical height (Abedi et al., 2011; Kim et al., 2011).

In this paper, higher geometric fidelity is achieved using MCNP – a general Monte Carlo N-Particle transport code-version5 (X-5 Monte Carlo Team, 2003). Not only is the double heterogeneity treated but also the truncation of CFPs and Pebbles is avoided. The unequal ratio of fuel and dummy pebbles and experimental packing fraction are all modeled correctly.

The paper is organized as follows. The HTR-10 characteristics are briefly introduced in Section 2. Three stages of modeling methodology are discussed in Section 3. Section 4 includes the results of some benchmark problems used to validate the developed model. Finally, in Section 5, the results are summarized.

2. A brief description of HTR-10

HTR-10 is a 10 MWth research reactor fueled with pebbles. The pebbles are 6 cm in diameter. Each fuel pebble contains about 8335 TRISO particles on average. TRISO particles are made up of 17% enriched UO_2 kernels coated with a low density buffer layer, an inner Pyrolytic Carbon (PyC) layer, an intermediate Silicon Carbide (SiC) layer and an external pyrolytic carbon layer. The buffer has a lower density than the other layers to absorb fission products. The SiC layer is an excellent barrier to retain radioactive gaseous and metallic fission products. At full power, the nominal volume of the core is 5 m^3 and contains 27,000 pebbles. The core is 180 cm in diameter and 197 cm in average height. Graphite bricks are used as the axial and radial reflectors. These bricks also used as thermal isolation and fast neutron shielding. The thickness of the side reflector is 100 cm. There is a conical region at the lower part of the side reflector in order to make the pebbles flow easily to the fuel discharge tube and avoid a stagnant corner in the core. One of the advantages of this reactor is on-line refueling. This requires a fuel discharge tube located at the bottom portion of the core. There are ten control rod channels, three irradiation channels, and seven absorber ball channels are located in the reflector. Dummy pebbles are also spherical and made up of graphite to provide extra moderation. The size of these dummy pebbles is identical to the fuel pebbles. The ratio of fuel pebbles to dummy pebbles is 57:43. Additionally, there are twenty circular channels for helium flow for cooling purposes. It can achieve a higher thermodynamic efficiency by increasing the outlet temperature without changing the reactor pressure by using helium (a noble gas) as a coolant (Abedi et al., 2011). Other design characteristics of HTR-10 may be found, in detail, in IAEA (2003).

It should be noted that before the initial core loading, some parameters were changed from the initial benchmark specification and summarized in Table 1.

3. Modeling methodology

The neutronic simulation of the HTR-10 reactor core using MCNP5 and MATLAB programming is a three-state process that is explained in this section. The input file for the MCNP5 code is generated by MATLAB and then the MCNP5 input file is run manually.

3.1. Fuel pebble modeling

In the first stage, the pebble is modeled. Each HTR-10 fuel pebble has 8335 particles on average and located randomly within the fuel region of the pebble (outer radius 5 cm). The expanded “FILL” card in 3D (27 × 27 × 27) hexahedral lattice of MCNP5 code is used to locate TRISO particles and eliminate truncated ones. First, TRISO particles are modeled and as a “UNIVERSE” are inserted into a hexahedral lattice in the form of SC structure. Truncated particles are then eliminated visually. Finally, using MATLAB, 25,005 (3× 8335) random numbers are generated representing each particle’s coordinates with a specific deviation (maximum allowed deviation is 0.0515 cm). Fig. 1 shows the simulated fuel pebble.

It is interesting to note that MCNP5 code has a stochastic geometry capability with “URAN” card. This feature provides a