An Exact MCNP Modeling of Pebble Bed Reactors

Amin Abedi, Naser Vosoughi, Mohammad Bagher Ghofrani

Abstract—Double heterogeneity of randomly located pebbles in the core and Coated Fuel Particles (CFPs) in the pebbles are specific features in pebble bed reactors and usually, because of difficulty to model with MCNP code capabilities, are neglected. In this study, characteristics of HTR-10, Tsinghua University research reactor, are used and not only double heterogeneous but also truncated CFPs and Pebbles are considered. Firstly, 8335 CFPs are distributed randomly in a pebble and then the core of reactor is filled with those pebbles and graphite pebbles as moderator such that 57:43 ratio of fuel and moderator pebbles is established. Finally, four different core configurations are modeled. They are Simple Cubic (SC) structure with truncated pebbles, SC structure without truncated pebble, and Simple Hexagonal (SH) structure without truncated pebbles and SH structure with truncated pebbles. Results like effective multiplication factor ($k_{\text{eff}}$), critical height, etc. are compared with available data.

Keywords—Double Heterogeneity, HTR-10, MCNP, Pebble Bed Reactor, Stochastic Geometry.

I. INTRODUCTION

Nowadays, nuclear energy because of worldwideneeds to more and new energy resources and environmental aspects, is one of the best candidates. Anyhow, there are some problems facing nuclear energy. The most important one is the safety aspects. The worry about an accident happening either because of human error or due to a terrorist attacker because of a natural disaster is inevitable. Modern reactors, the so called Generation IV reactors, are designed to cover these aspects. High Temperature Reactors (HTRs) are one of these types of reactors. A possible design of HTRs is pebble bed reactor. In pebble bed reactors, the nuclear fuel is contained in pebbles of graphite instead of metallic rods [1]. These reactors are inherently safe. In other words, passive safety features of this type of reactor are demonstrated practically. For example, it is illustrated that in accidents such as LOCA or withdrawal of control rods without scram, the large negative temperature coefficient of reactivity and temperature margin will shut the reactor down automatically. Meanwhile, the large heat capacity of its core prevents excessive increases in fuel temperature and maintains the maximum fuel temperature below limit [2]–[3]. To demonstrate features and illustrate characteristics of any reactors, they must be simulated by relevant nuclear codes. To simulate pebble bed reactors exactly, double heterogeneous of the reactor must be considered. Fuel pebbles in this reactor consist of Coated Fuel Particles (CFPs), TRISO particles, which are embedded in a graphite matrix stochastically. Also, the reactor core is stochastically filled of fuel and dummy pebbles with a specific ratio. These two stochastic geometries are the so called double heterogeneous of these types of reactors.

II. HTR-10 DESCRIPTION

HTR-10 is a research reactor with 10 MWt power output, which employed fuel pebbles. These pebbles are 6 cm in diameter. Each fuel pebble contains about 8335 TRISO particles. TRISO particles are made of 17% enriched UO$_2$ kernels coated with two inner pyrolytic carbon (PyC) layers, an intermediate SiC layer and an external pyrolytic carbon layer [10]. Densities of PyC layers are different. The one is 1.0 g/cm$^3$, which is embedded in a graphite matrix stochastically. Also, Monte Carlo MCNP code is used for this modeling. This code can calculate eigenvalues for the critical systems and model complex geometries [9].
also spherical and made of graphite and serves as moderator. The size of these dummy pebbles is identical to the fuel pebbles. The ratio of fuel pebbles to dummy pebbles is 57:43[10]. Additionally, there are twenty circular channels for helium flow for cooling purposes. By using helium, a noble gas, as a coolant can have higher efficiency by increasing output temperature without increasing the reactor pressure [11]. Design characteristics of HTR-10 can be found in [12].

III. SIMULATION DIFFICULTIES

There are two types of difficulties for simulation of pebble bed reactors with MCNP code. The first type of problems is related to geometry of these reactors. For simulating these reactors exactly, double heterogeneous of them must be considered. For example, for HTR-10 initial criticality, approximately 17,000 fuel and dummy pebbles are located in the core randomly. These fuel pebbles also have 8335 TRISO particles that are embedded in a graphite matrix stochastically. Especially, in this reactor the ratio of fuel and dummy pebbles are not the same. This feature makes it more difficult.

Second type of problems is MCNP5-1.51 code limitations. For example, the maximum number of cells that can be used is 99,999. So, for simulating each TRISO particle of each fuel pebble individually, number of cells (8,335 × 0.57 × 17,000) will be exceeded from limited value (99,999) of MCNP5-1.51 code.

IV. HTR-10 MODELING

A. Fuel Pebble Modeling

In this section, modeling of first heterogeneous, randomly located TRISO particles in the fuel pebbles will be explained.

Real pebbles don’t have truncated TRISO particles and these particles that are 8335 on average, located randomly in fuel pebbles. Expanded fill card in 3D (27×27×27) hexahedral lattice of MCNP code is used for locating TRISO particles and eliminating truncated particles. First, TRISO particles are modeled and as a universe inserted in a hexahedral lattice in the form of Simple Cube (SC). Then truncated particles are eliminated visually. Finally, using MATLAB programing and producing 25005 (3 × 8335) random numbers, each particle coordinates with specific deviation (0.0515 cm) are transformed. Figure 1 shows this simulated fuel pebble.

It is interesting to note that MCNP5 code has a stochastic geometry capability with URAN card [13]. This feature provides a random transformation when a neutron enters a lattice containing an embedded universe. This feature has some pros and cons. Because it doesn’t have stochastic geometry plotting capability, users must be very careful not to use it incorrectly. Additionally, it can be used in lattice elements which its embedded universe has a specific deviation. So, this feature can’t be used for modeling of pebbles in the core [9].

B. Core modeling

According to use which type of unit cell structure and eliminate or not to eliminate the truncated pebbles, the reactor core can be filled with different packing fractions. In this section, four models with different packing fractions and same loading heights will be explained as shown in Figure 2. In these models, fuel and dummy pebbles with 57:43 ratio are located randomly in the core.

In this study, both simple hexagonal (SH) structure and simple cubic (SC) structure are used. These structures have a specific packing fraction but by eliminating the truncated pebbles their packing fractions will be reduced. For example,
packing fractions of SC structure with or without truncated pebbles are 52.3% and 49.8% respectively. Similarly, packing fraction of SH structure with and without truncated pebbles are 60.46% and 56.9% respectively. It is noticeable because of similarity of SH structure with truncated pebbles with average experimental packing fraction 61% , best results from this configuration is expected.

Full core modeling of HTR-10 with detail specifications is illustrated in Figure 3. In this figure, vertical and horizontal cross-section of reactor and zoomed views of them illustrated.

Fig. 3 HTR-10 reactor with MCNP: (a) vertical cross-section (b) horizontal cross-section (c) vertical cross-section of a pebble (d) horizontal cross-section of a pebble (e) aTRISO particle
In these zoomed views, stochastic distribution of dummy pebbles (dark pebbles) and fuel pebbles (light pebbles) are obvious. Additionally, stochastic distribution of TRISO particles in a fuel pebble by zooming one of them in two different cross-sections is shown. Finally, a TRISO particle with different layers is zoomed. Assumptions used in this simulation comprise of initial cold core, withdrawal of control rods and filling of bottom cone zone by only dummy pebbles and 293.6 °K, temperature of used cross sections.

V. SIMULATION RESULTS

A. Fuel Pebble Simulation Results

At the first stage of simulation, a fuel pebble by assuming white boundary and other assumptions as in [12], is simulated. The results are presented in Table I. Effective multiplication factor in pebbles with regularly distributed TRISO particles is a little less than stochastic distributed ones (see Table I). Also, both stochastic distributed ones show the same results according to their standard deviations. But only difference between these two methods is stochastic geometry plotting capability of method of this study comparing to MCNP5 stochastic capability.

<table>
<thead>
<tr>
<th>type</th>
<th>$K_{eff}$</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo2(1D&amp;172 energy group)*</td>
<td>1.71926</td>
<td>-</td>
</tr>
<tr>
<td>Pebble with regularly distributed TRISO particles</td>
<td>1.76404</td>
<td>0.00006</td>
</tr>
<tr>
<td>Pebble with stochastic distributed TRISO particles using method of this study</td>
<td>1.76480</td>
<td>0.00006</td>
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<tr>
<td>Pebble with stochastic distributed TRISO particles using URAN card of MCNP5</td>
<td>1.76485</td>
<td>0.00005</td>
</tr>
</tbody>
</table>

* From [12]

In these zoomed views, stochastic distribution of dummy pebbles (dark pebbles) and fuel pebbles (light pebbles) are obvious. Additionally, stochastic distribution of TRISO particles in a fuel pebble by zooming one of them in two different cross-sections is shown. Finally, a TRISO particle with different layers is zoomed. Assumptions used in this simulation comprise of initial cold core, withdrawal of control rods and filling of bottom cone zone by only dummy pebbles and 293.6 °K, temperature of used cross sections.

B. HTR-10 Core Simulation Results

As mentioned above, four different core configurations are modeled. Figure 4 shows core multiplication factor vs. packing fraction. Here in these models, loading height is 126 cm. Also, SH structure with truncated pebbles has the best result in comparison with other models as seen in Figure 4. So, for next modeling SH structure with truncated pebbles is used. The ratio of fuel pebbles to dummy pebbles is 57:43. So besides of considering the double heterogeneous, this special feature must be considered. For this, a uniform random number generator is used to produce number between 0 and 1. If those numbers is smaller than 0.43 relevant lattice cells will be filled with dummy pebbles and if they are larger than 0.43 relevant lattice cells will be filled with fuel pebbles. This method is a stochastic method. So, the results have a deviation that is illustrated in Figure 5. In this figure, effective neutron multiplication factor vs. void faction is shown. The loading height in this modeling is the same as experimental critical height (123.06 cm).

Finally, SH structure with truncated pebbles is used to show the effect of exact TRISO particle modeling in the fuel pebbles. At first stage, fuel pebbles with regularly distributed CFPs are filled and the reactor core is stochastically filled with different loading heights. Then, the pebbles are filled with randomly distributed CFPs and the reactor core is stochastically filled with different loading heights. The results are given in Table II.

From Table II, it can be found that near criticality, effective neutron multiplication factors of this study and VSOP code results are equivalent to each other by considering its standard
deviations. In addition, this fact can be seen in Figure 6. In this figure, effective neutron multiplication factor of core which is modeled using SH structure with truncated pebbles is plotted vs. different loading heights. Pebbles in this modeling are filled with randomly distributed CFPs. Also, the results between using homogenized pebbles and exact pebbles in the core are significant. In other words, using homogenized pebbles are not recommended at all.

VI. CONCLUSION

An exact model of HTR-10 reactor core as a pebble bed reactor is simulated using MCNP code. In this model, double heterogeneity of randomly located pebbles in the core and CFPs in the pebbles are considered. In addition, unequal ratio of fuel and dummy pebbles are considered.

Four different configurations comprise of SC structure with truncated pebbles, SC structure without truncated pebble, SH structure without truncated pebbles and SH structure with truncated pebbles are modeled. From fuel pebble simulation results can be found that for calculating effective neutron multiplication factor, modeling of randomly distributed of CFPs can be ignored. Results of four different core configurations show that effective neutron multiplication factor is very sensitive to packing fraction. Indeed, this fact is important by knowing that some disasters like earthquake can affect on packing fraction of this type of reactor. Moreover, SH structure with truncated pebbles because of its packing fraction that is close to experimental magnitude, has the best agreement with available data from VSOP code and experimental results.

REFERENCES


