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An Exact MCNP Modeling of Pebble Bed Reactors

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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_{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 happeningeither because of human error or due to a terrorist attackor because of a natural disaster is inevitable. Modern reactors, the so called Generation IV reactors, are designed to cover these issues. High Temperature Reactors (HTRs) are one of these types of reactors. A possible design of HTRs is pebblebed 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 reactormust be considered. Fuel pebbles in this reactor consist of Coated Fuel Particles (CFPs), TRISO particles, whichare 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 geometriesare the so called double heterogeneous of these types of reactors.In several papers, these two heterogeneous are neglected for the sake of simplicityand CFPs in pebbles and pebbles in the core are distributed regularly. In some of them, truncated CFPs and pebbles are not eliminated as well [4]-[6].In some others only one of these features are considered [7]-[8]. In this study, not only the double heterogeneous but also the truncated CFPs and Pebbles are considered. HTR-10 is a pebble bed research reactor which is selected as a test reactor in this study. This reactor is built and operated in Institute of Nuclear Energy and Technology (INET), Tsinghua University, Beijing, China. Also, Monte Carlo MCNP code is used for this modeling. This code can calculate eigenvalues for the critical systems and model complex geometries [9].

II. HTR-10 DESCRIPTION

HTR-10 is a research reactor with 10MWt 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 around the kernel has a lower density than others to be a porous media for fission products. SiC layer is an excellent barrier to retain radioactive gaseous and metallic fission products [4]. The nominal volume of the core is 5 m^3 and can contain 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 conus region at the low part of the side reflector in order to make the pebbles flow easily and avoid a dead corner in the core [11]. One of the advantages of this reactor is to have on-line refueling. So, there is a fuel discharge tube located at the bottom portion of the core. There are vertical channels in the side reflector. There are ten control rod channels, three irradiation channels, and seven absorber ball channels are located in the reflector. Dummy pebbles, are

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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 cells. 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. Figure1 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*

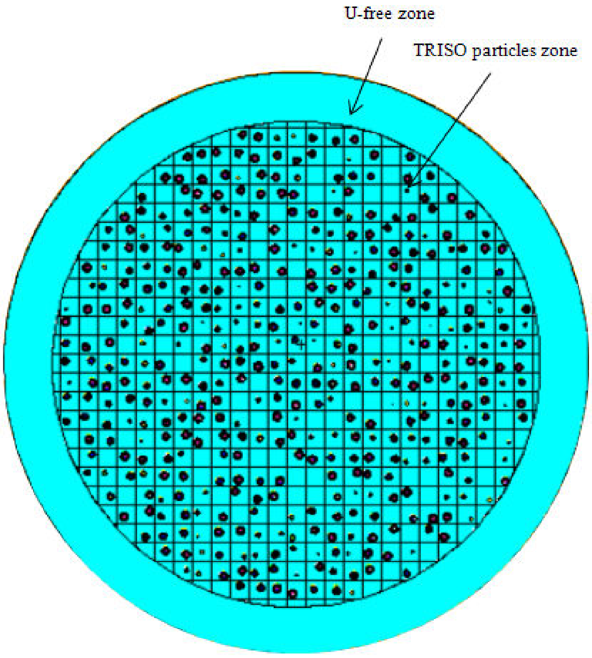

Fig. 1 Random located TRISO particles in a fuel pebble

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 randomlyin 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,

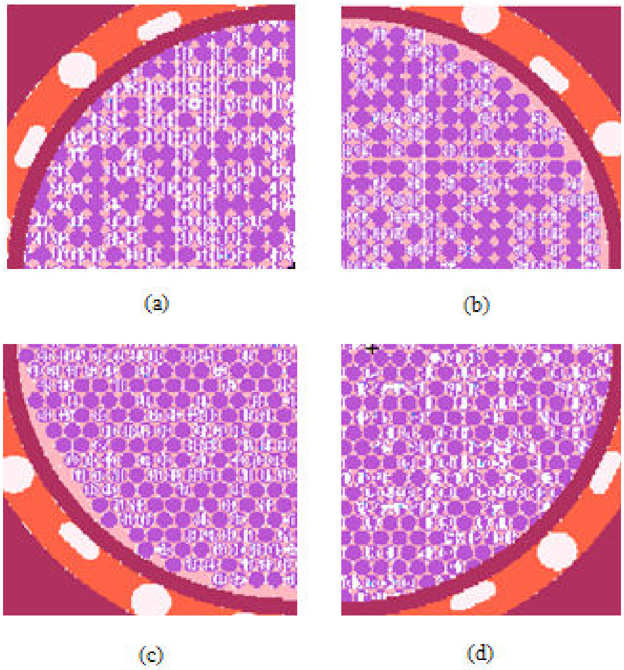
(a) (b)
(c) (d)

Fig. 2 Four different models of pebbles distribution in the core: (a) SC structure with truncated pebbles (b)SC structure without truncated pebble (c) SH structure without truncated pebbles (d) SH structure with truncated pebbles

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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. Inthis figure, vertical and horizontal cross-section of reactor and zoomed views of them illustrated.

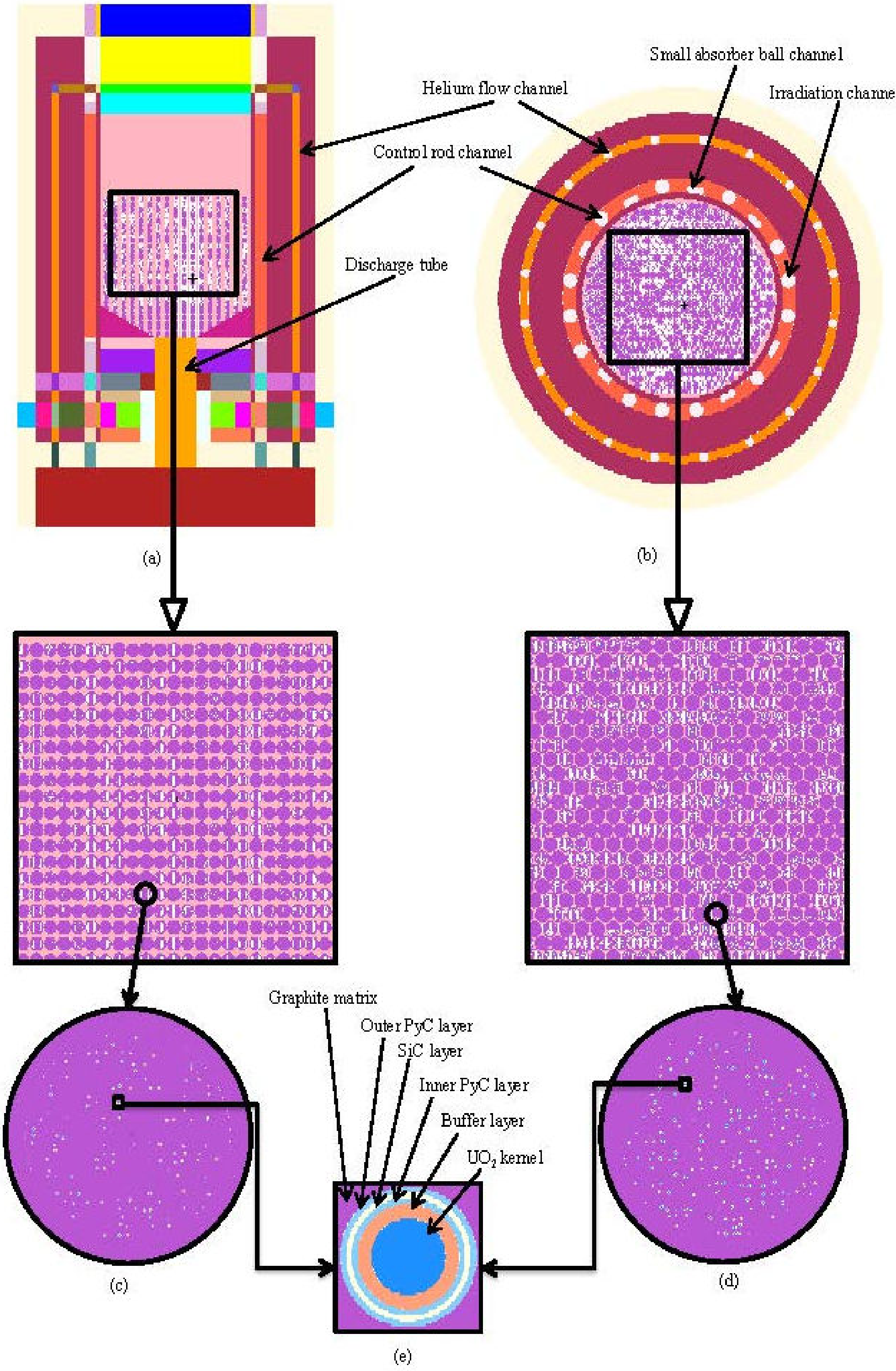

Fig. 3 HTR-10 reactor with MCNP: (a) vertical cross-section (b) horizontal cross-section (c) vertical cross-section of a pebble (d) horizontal cross-section of a pebble (e) aTRISO particle

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TABLE I
PEBBLE EFFECTIVE MULTIPLICATION FACTOR

type	K_{EFF}	standard deviation
Apollo2(1D&172 energy group)*	1.71926	-
Pebble with regularly distributed TRISO particles	1.76404	0.00006
Pebble with stochastic distributed TRISO particles using method of this study	1.76480	0.00006
Pebble with stochastic distributed TRISO particles using URAN card of MCNP5	1.76485	0.00005

* 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 pebbles 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 and293.6 ˚K, temperature of used cross sections.

V. SIMULATION RESULTS

A. Fuel PebbleSimulation 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.

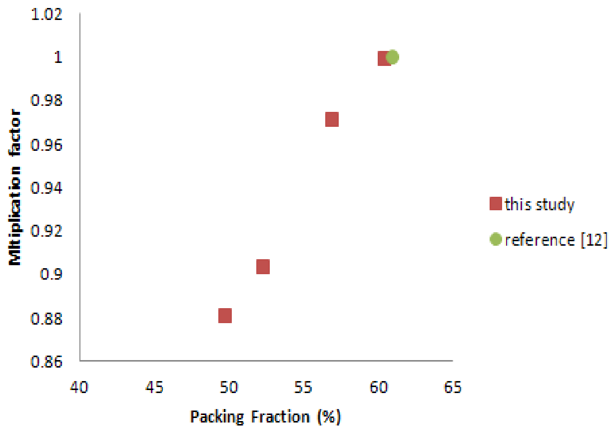

Fig. 4 Multiplication factors vs. packing fractions

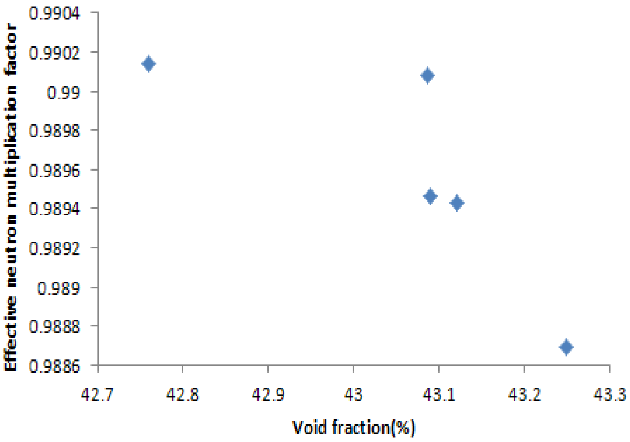

Fig. 5 Neutronmultiplication factor vs.void fractions

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 pebbleshas 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, auniform 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 pebblesis 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.

In this table, the results are compared with the results of MCNP and VSOP computer codes which are available in [12]. VSOP is a computer code system for comprehensive numerical simulation of the physics of thermal reactors. It is used for processing of cross sections, neutron spectrum evaluation, neutron diffusion calculation, thermal hydraulics, fuel burn up, reactor control, etc. it is interesting to note that the thermal hydraulic part either steady state or time-dependent is only for HTRsin two spatial dimensions. Also, this code can simulate the reactor operation from initial core to the equilibrium core [14].

From Table II, it can be found that near criticality, effective neutron multiplication factors of this study and VSOP code results are equivalent toeach other by considering its standard

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TABLE II
HTR-10 INITIAL CRITICALITY MULTIPLICATION FACTOR

Core Height(cm)	Methods	K_{EFF}	Standard Deviation
90	this study (regularly distributed CFPs)	0.8613	0.00028
	this study (randomly distributed CFPs)	0.86073	0.00029
	MCNP*	0.86062	0.00083
	VSOP*	0.86379	-
120	this study (regularly distributed CFPs)	0.98108	0.00029
	this study (randomly distributed CFPs)	0.98114	0.00029
	MCNP*	0.98148	0.00088
	VSOP*	0.98216	-
126	this study (regularly distributed CFPs)	0.99981	0.00029
	this study (randomly distributed CFPs)	1.00049	0.00028
	MCNP*	0.99965	0.00091
	VSOP*	1.00060	-

* From [12]

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.

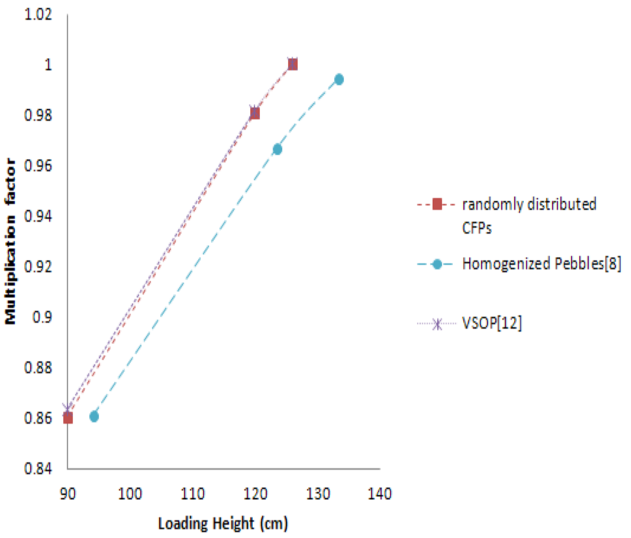

Fig. 6 Core multiplication factors vs. loading height

VI. CONCLUSION

An exact model of HTR-10 reactor core as a pebble bed reactor is simulated using MCNP code. In this model,doubleheterogeneity 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 pebblesbecause of its packing fraction that is close to experimental magnitude, has the best agreement with available data from VSOP code and experimental results.

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