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First Criticality and Uncertainty Analysis of the HTR-PM using MCS

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1. Introduction

The HTR-PM is a scale-up of the HTR-10, one of the generation IV nuclear power plants with a gas-cooled typed reactor. It was built in China and it has reached its first criticality. This gives a chance to perform calculations by UNIST in-house Monte Carlo code MCS [1] and validates it.

The results of computer calculations used to analyze the benchmarks of HTR-10 are far from a well-established art [2]. Furthermore, the size of HTR-PM will add complexity, not to mention the double heterogeneity caused by the Tri-structural Isotropic (TRISO) particles and pebbles. This paper presents the multiplication factor (k_{eff}) as a function of core loading height. Some parameters, including the cross-section library, graphite material, radius of the fuel zone, and the randomness of the mixed pebbles, were analyzed to study the uncertainty.

2. Methods and Results

In this section, some of the techniques used to model the HTR-PM and important parameters are described.

The reactor has a shape of a cylinder and spherical fuel and graphite as a moderator. There are three types of channels: 24 control rod channels, 6 absorber ball channels, and 30 cold helium channels that are located in graphite reflectors. The fuel pebble consists of randomly packed of 11672 TRISO particles embedded in a graphite matrix. For simplicity, the TRISO positions are considered to be fixed. For the initial core loading, graphite pebbles will be first loaded into the discharge tube and the bottom region of the reactor. Then, the mixed pebbles, which are a mixture of fuel pebbles and graphite pebbles, will be loaded until the reactor reaches the first criticality. The packing fraction of the entire pebbles is 0.61. The positions of TRISO and pebbles are externally determined by python scripts using random sequential packing for TRISO and close random packing based on the Jodrey Tory algorithm [3] for pebbles. There are no overlapping particles and pebbles in this random packing. The fuel pebbles and graphite pebbles are randomly selected with a ratio of 7:8 by the python numpy random module, both permutation and shuffle.

All physical parameters, such as the detailed geometry of the reactor and the materials, are provided in [4]. The cone shape of the core bottom is converted into a cylindrical shape without changing the actual volume. It should be noted that this work is modeled in accordance with the base conditions given in [4]. It is assumed that the reactor is at 293.6 K and filled with air.

Some important parameters used in this work are the number of graphite pebbles that filled the reactor to a height of 605 cm is 234956 (including in the discharge tube) and it has a fixed position for all loading heights of mixed pebbles. The impurity represented by equivalent boron concentration (EBC) in uranium is 0.5 ppm. The percentage of boron is as follows 19.9% ^{10}B and 80.1% ^{11}B. As for nuclear graphite used in HTGRs, it usually has a graphitization degree of around 80–90% [5], so in this case, graphite with 10% porosity is used.

The MCS simulations were executed on a Linux cluster (Intel(R) Xeon(R) CPU E5-2680 v4 @ 2.40GHz) with 28 cores. The simulations were performed for 500 active and 50 inactive cycles with two million neutrons and it took not more than 32 hours for each loading height.

Results from the MCS code with ENDF/B-VIII.0 are compared with preliminary benchmarks of the HTR-PM from the RMC Monte Carlo code and PANGU [4] as well as the experimental data [6].

Figure 1 illustrates the fuel pebble contains TRISO particles. Each particle has pyrolytic carbon, silicon carbide and buffer as a coating. Figures 2 and 3 illustrate the full core layout of the HTR-PM. The yellow color represents the fuel pebbles and the grey color represents the graphite pebbles.

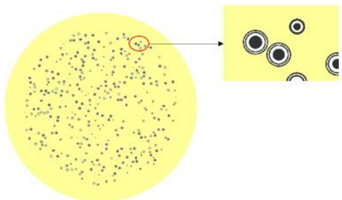

Fig. 1. TRISO particles in fuel pebble

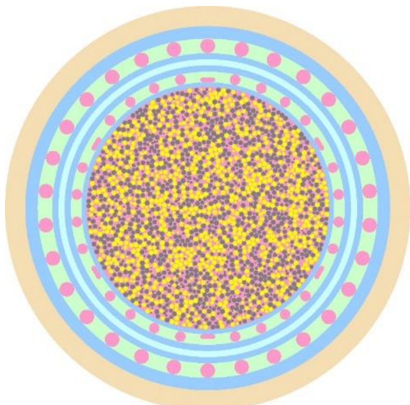

Fig. 2. Radial view of the HTR-PM

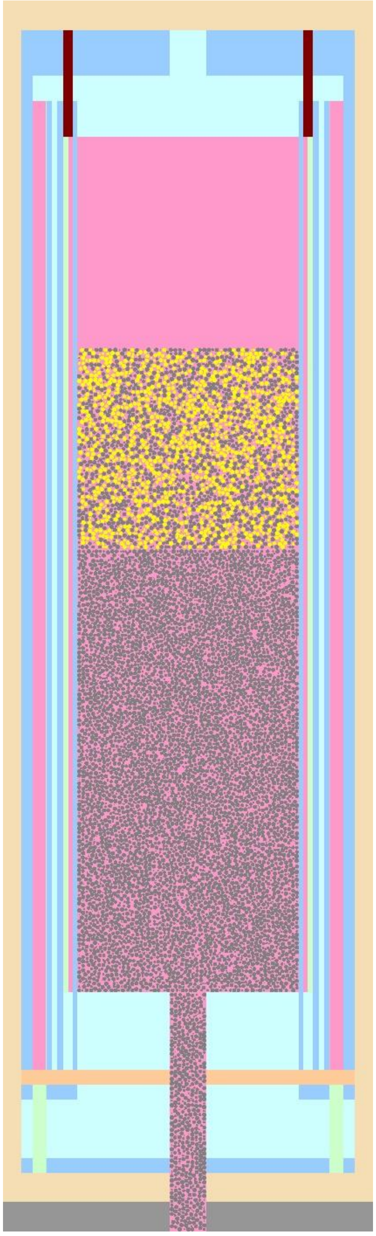

Fig. 3. Axial view of the HTR-PM

3. Results

3.1. Comparison calculation with the preliminary benchmarks

The k_{eff} at different loading heights of mixed pebbles by MCS code and RMC code are shown in Table I. The comparison of k_{eff} is expressed by reactivity difference using equation 1 as follows:

$$\Delta\rho = \frac{1}{k_{eff}^{reference}} - \frac{1}{k_{eff}^{MCS}} \quad (1)$$

In general, the difference in k_{eff} is below 0.12% for all loading heights. This shows that MCS results agree with both codes, specially with PANGU since the maximum difference in k_{eff} between MCS and PANGU is 0.09% while MCS and RMC is 0.11%. Further investigation suggests that the positions of pebbles caused the discrepancies. This will be further discussed in 3.3.

By using interpolation, the first criticality achieves with the height of mixed pebbles equals 271.4 cm with the corresponding number of mixed pebbles is 103861. The experimental data [6] shows the first criticality is achieved when the number of mixed pebbles is approximately 102300.

3.2. Uncertainty analysis by several different parameters.

Changing the cross-section library, graphite material and radius of the fuel zone can significantly affect the k_{eff}. In this section, the HTR-PM with 275 cm loading height of mixed pebbles was analyzed. Results are shown in Table II.

Graphite with 10% porosity is not available in ENDF VII, so for this case, the crystalline graphite is used for both library ENDF/B VII.0 and ENDF VIII.0. A noticeable discrepancy is given between the libraries. The result given by ENDF/B VII.0 overestimated the k_{eff} by 1.39% or in this case is 1412 pcm. The significant change of the capture cross-section of graphite in ENDF/B VIII.0 and due to the fact that the majority of the HTR-PM materials consist of graphite make this discrepancy looks obvious. This result is in agreement with other previous work [7].

Table I: List of k_{eff} by RMC, PANGU and MCS for various loading heights.

Loading height of mixed pebbles (cm)	Number of mixed pebbles	k_{eff}			Δρ (%) with RMC	Δρ (%) with PANGU
		RMC (±10 pcm)	PANGU	MCS (±2 pcm)		
220	84182	0.94760	0.94648	0.94674	-0.10	0.03
250	95662	0.98130	0.98083	0.98075	-0.06	-0.01
275	105228	1.00432	1.00358	1.00321	-0.11	-0.04
300	114794	1.02293	1.02232	1.02201	-0.09	-0.03
330	126274	1.04095	1.04075	1.04003	-0.08	-0.07
385	147319	1.06638	1.06634	1.06534	-0.09	-0.09
440	168365	1.08496	1.08485	1.08385	-0.09	-0.09

The library ENDF/B VIII.0 has three types of graphite that are related to the porosity of 0% which also means 100% graphitization degree, 10% and 30%. By comparing the 0% porosity and the 10% porosity, the result showed that graphite with 10% porosity has higher k_{eff} by 0.34% or in this case is 344 pcm. The difference is likely caused by the thermal neutron scattering cross-section. As mentioned in [8], if simply assuming a 100% graphitization degree in HTR-PM criticality calculation, k_{eff} can be underestimated by 0.2%~0.4%. Result on HTR-10 when the porosity is assumed in all graphite structures, significant differences of above 300 pcm for 10% porosity is observed [9].

It found out that there is an optimal pebble design that can give the highest k_{eff} depending on the size and power of the reactor [10]. Reducing the radius of the fuel zone from 2.5 cm to 2.3 cm can increase the k_{eff} by 0.09% or in this case is 94 pcm. As a matter of fact, X-Ray photographs show that the actual fuel zone radius is slightly less than 2.5 cm [4].

Table II: Uncertainty analysis

Parameters	Change from/to	Δρ (%)
Library ENDF/B	VIII.0/ VII.0	1.39
Graphite porosity (%)	0/10	0.34
The radius of fuel zone (cm)	2.5 /2.3	0.09

3.3. Uncertainty analysis by the randomness of mixed pebbles.

Fifty samples of only the mixed pebbles were used to quantify the uncertainty affected by the randomness of the mixed pebbles. It is when pebbles have the same position but fuel and graphite pebbles are chosen differently, as shown in Figure 4.

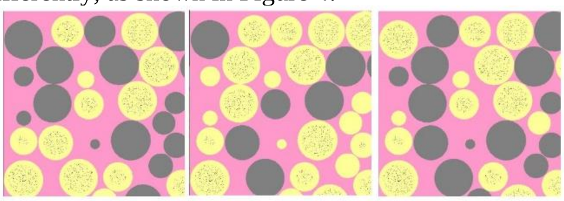

Fig. 4. Mixed pebbles with a different selection of fuel and graphite

The mixed pebbles with 250 cm loading height was chosen because it gave the smallest discrepancy among all loading heights. The numbers of fuel and graphite pebbles are the same for all samples, which are 44642 and 51020. The simulations were performed with black boundary condition for 120 active and 30 inactive cycles with one million neutrons. A histogram of results is shown in Figure 5. The results show that the k_{eff} ranged between 0.72959 to 0.73638 with a maximum standard deviation of 8 pcm.

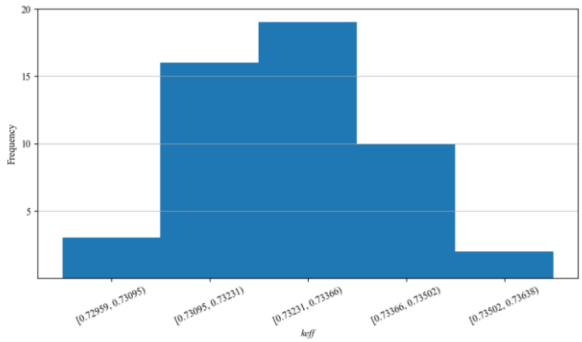

Fig. 5. Histogram of k_{eff} with a different selection of fuel and graphite

It is important to mention that the lowest k_{eff} is responsible for 0.97773 k_{eff}, while the highest k_{eff} is responsible for 0.98075 k_{eff} in the whole reactor. Both are with two pcm standard deviations. An uncertainty of 302 pcm is given by the whole reactor model. Note that in the only mixed pebbles problem, the range of k_{eff} is larger than in the whole reactor due to the absence of a reflector.

4. Conclusions

A model of the HTR-PM can be simulated by MCS. The results of k_{eff} agree well with various loading heights compared with the preliminary benchmarks. The number of mixed pebbles is also close compared with the experimental result. However, the effects of the cross-section library, graphite material and radius of the fuel zone cannot be ignored.

Further study found that the randomness of mixed pebbles significantly affects the k_{eff}. So, it would be challenging to accurately find a k_{eff} that agrees well with experimental data without knowing the details position of the pebbles.

Acknowledgments

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REFERENCES

[1] H. Lee, W. Kim, P. Zhang, A. Khassenov, Y. Jo, D. Lee, Development Status of Monte Carlo Code at UNIST, Korean Nuclear Society Spring Meeting, 2016.
[2] W. K. Terry, S. S. Kim, L. M. Montierth, J. J. Cogliati, and A. M. Ougouag, Evaluation Of The HTR-10 Reactor As A Benchmark For Physics Code QA, International Reactor Physics Experiment Program Working Group Meeting, INL, 2005.
[3] W. S. Jodrey, and E. M. Tory, Computer Simulation of Close Random Packing of Equal Spheres, Physical Review A, Vol.32, No.4, 1985.
[4] D. She, B. Xia, J. Guo, C. L. Wei, J. Zhang, F. Li, L. Shi, and Z. Y. Zhang, Prediction calculations for the first criticality

of the HTR-PM using the PANGU code, NUCL SCI TECH, 2021.
[5] H. Wu, R. Gakhar, A. Chen, C. P. Marshall, and R. Scarlat, Comparative Analysis of Microstructure and Reactive Sites for Nuclear Graphite IG-110 and Graphite Matrix A3, INL, 2019.
[6] R. Li, Z. Liu, Z. Feng, J. Liang, and L. Zhang, High-Fidelity MC-DEM Modeling and Uncertainty Analysis of HTR-PM First Criticality, Frontiers in Energy Research, 2022.
[7] F. Bostelmann, G. Ilas, W. A. Wieselquist, Key Nuclear Data Impacting Reactivity in Advanced Reactors, ORNL, 2020.
[8] L. Zhang, D. She, L. Shi, Influence of graphitization degree of nuclear graphite on HTGR reactor physics calculation, Annals of Nuclear Energy, 2020.
[9] F. Bostelmann, A. M. Holcomb, W. J. Marshall, V. Sobes, B. T. Rearden, Impact of the ENDF/B-VIII.0 Library on Advanced Reactor Simulations, ORNL
[10] A. M. Ougouag, H. D. Gougar, W. K. Terry, R. Mphahlele, and K. N. Ivanov, Optimal Moderation in the Pebble-Bed Reactor for Enhanced Passive Safety and Improved Fuel Utilization, PHYSOR 2004.