A HIGH-FIDELITY MULTIPHYSICS COMPUTATIONAL MODEL FOR PEBBLE BED GAS REACTOR BASED ON OPEN-SOURCE SOFTWARE

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INTRODUCTION

The primary objective of this study is to develop a comprehensive computational model to analyze a full-scale high-temperature gas-cooled Pebble Bed Reactor (HT-PBR). In the context of the HT-PBR, the pebbles encompass both the fuel and multiple safety layers of the reactor. Helium gas serves as the medium for transferring heat energy from the reactor by flowing through the porosity within the pebble structure. In HT-PBR, the pebbles continuously circulate through the system, being loaded into and passing through the reactor repeatedly. Consequently, the computational modeling of the HT-PBR reactor involves addressing multiple physics aspects, including reaction physics (neutronics), energy transfer between gas and pebbles, gas flow within the pebble bed, and the continuous recirculation of pebbles.

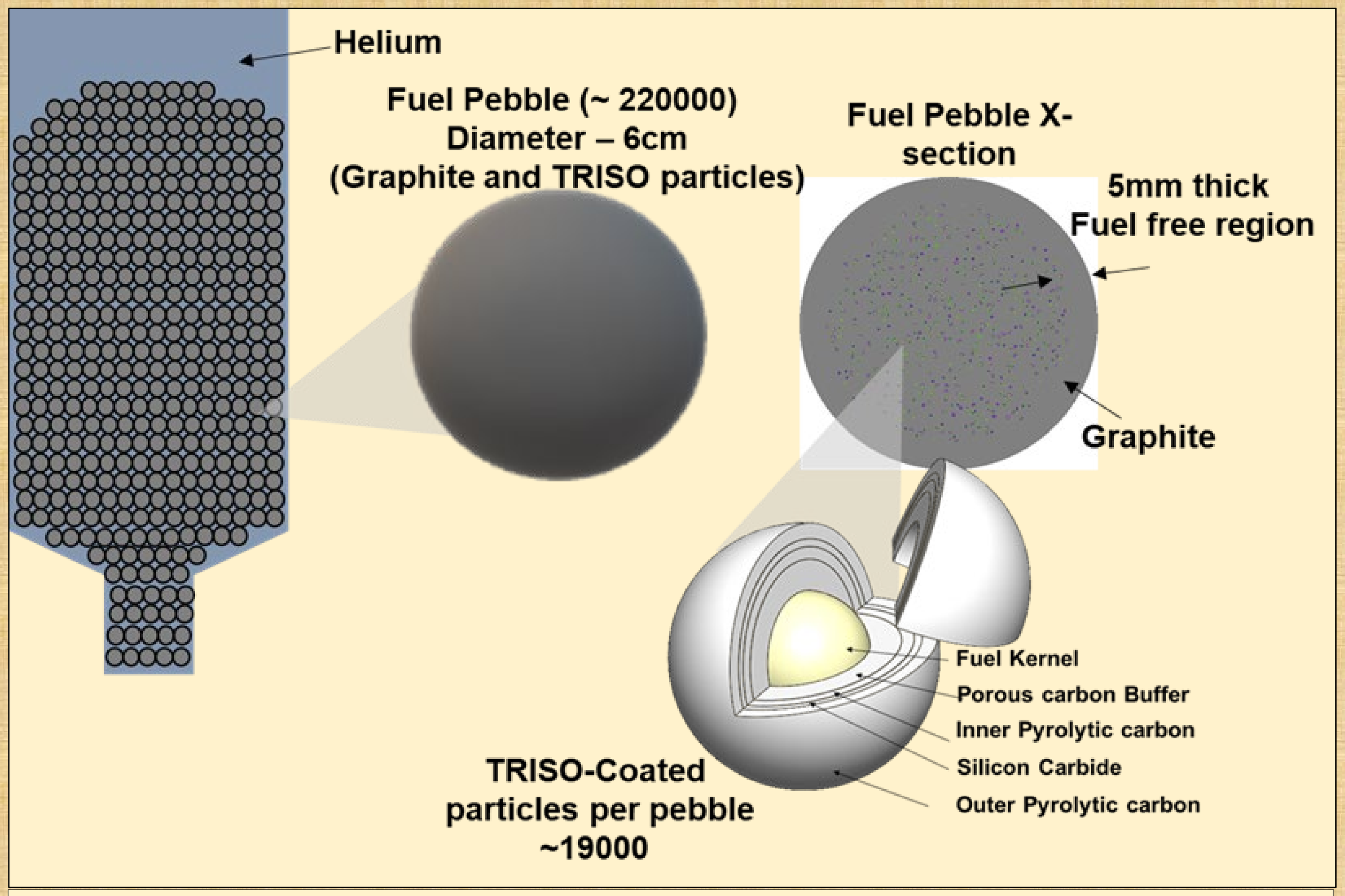

Figure 1. Schematic Overview of a HT-PBR.

Table 1. Pebble material composition and dimension.

Material	Density (g/cm³)	Composition (at.%)	Dimension (µm)
UCO Fuel	10.9	^{235}U: 0.05232 ^{238}U: 0.28101 ^{16}O: 0.49982 ^{17}O: 0.00019 C: 0.16667	425 (diameter)
Carbon Buffer	1.0	C: 1.0	100 (thickness)
PyC1	1.9	C: 1.0	40 (thickness)
PyC2	1.9	C: 1.0	40 (thickness)
SiC	3.2	C: 0.5 Si: 0.5	35 (thickness)
Graphite	1.75	C: 1.0	6 cm diameter with a 0.5 cm thickness non-fuel shell

METHODOLOGY

A high-fidelity **multiphysics** computational modeling and simulation platform is established for the HT-PBR analysis via purely open-source tools. Monte Carlo based method open-source code – OpenMC - is used in this work for **neutronics analysis**. OpenMC can handle fixed source, *k*-eigenvalue, and subcritical multiplication calculations on models. It offers numerous features that make it appealing for nuclear reactor analysis, including high performance, parallelism, versatility and modularity. The open-source CFD-DEM coupling software is employed for **pebble and gas fluid dynamics analysis**. CFD-DEM couples the PisoFOAM solver with the DEM code LIGGGHTS. The PisoFOAM is a finite volume based solver in OpenFOAM and is capable of solving incompressible, turbulent flow with the PISO algorithm.

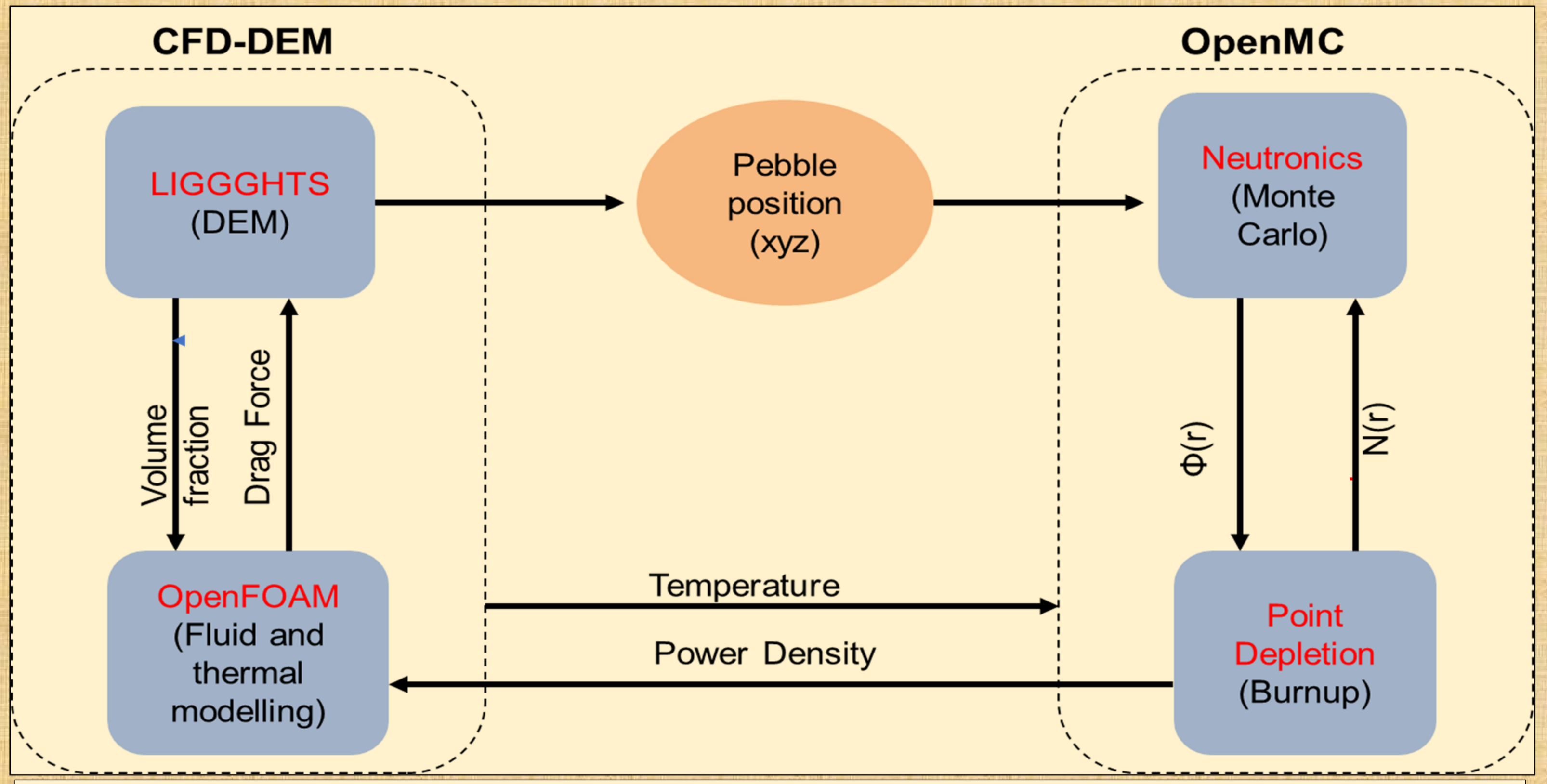

Figure 2. The flowchart between CFD-DEM and OpenMC.

RESULTS

The neutronics calculations were conducted at the pebble level and the whole core level. The multiplication factors (either k_∞ or k_{eff}) are reported in this work.

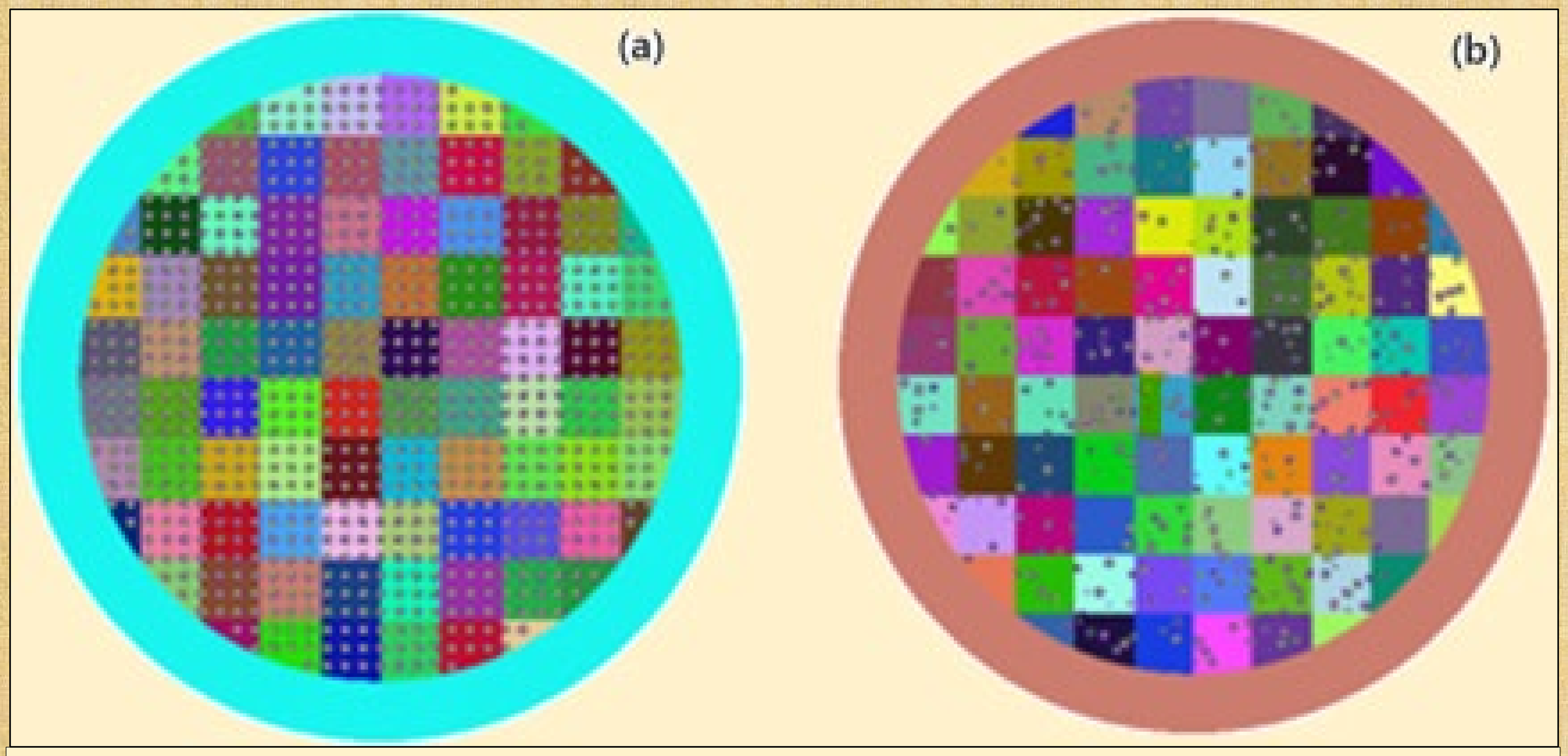

Figure 3. A 2D pebble model in OpenMC with (a) uniform and (b) random TRISO particle distributions.

Table 2. Neutronics results of a pebble.

Pebble Model		k_∞ (White B.C.)	k_∞ (Mirror B.C.)
Uniform particle distribution	MCNP	1.60743 +/-0.00008	1.61471+/-0.00004
	OpenMC	1.60818 +/- 0.00011	1.61560 +/- 0.00012
	Deviation	-0.00067	-0.00089
Random particle distribution	MCNP	1.61017 +/-0.00007	1.61723 +/-0.00006
	OpenMC	1.61025 +/-0.00011	1.61739 +/- 0.00012
	Deviation	0.00008	0.00016

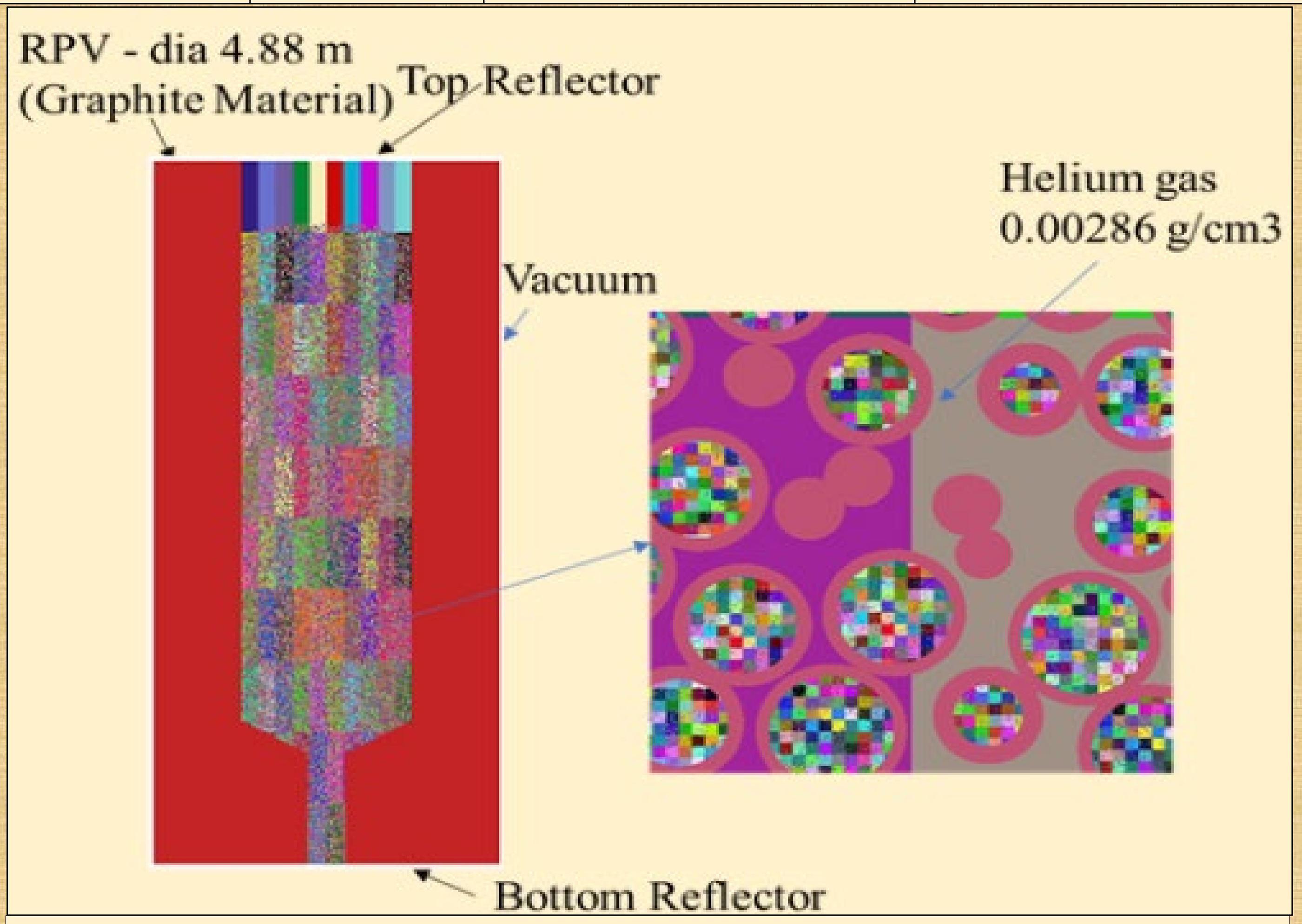

Figure 4. Configuration of the reactor core (left) and the fuel pebble (right) in the core.

Table 3. Steady-state whole core calculation result.

k_{eff}	Leakage fraction	Simulation time
1.39160 +/-0.00021	0.04780 +/- 0.00005	3 hours

CONCLUSIONS

This work provides a detailed description of a high-fidelity multiphysics analysis of a HT-PBR core utilizing a computational coupling scheme established by open-source software CFD-DEM and OpenMC. The positions of the moving pebbles are determined using the DEM based LIGGGHTS code and loaded into OpenMC, which performs the subsequent steady-state neutronics calculations. The work reports the steady-state neutronics operation results for an operational HT-PBR core based on the X-energy's Xe-100 design, which contains ~200,000 pebbles.

ACKNOWLEDGEMENT

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