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Numerical study of pebble recirculation in a two-dimensional pebble bed of stationary atmosphere using LB-IB-DEM coupled method

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ABSTRACT

The pebble bed is one type of the core of the high temperature gas-cooled reactor (HTGR), which is regarded as the candidate of the generation IV advanced reactor. It is important to explore the gas-pebble flow characteristics and the pebble recirculation under the helium atmosphere. In this work, we presented a lattice Boltzmann (LB) method – immersed boundary (IB) method – discrete element method (DEM) coupled approach to simulate a test facility of pebble bed under the recirculation mode of operation. After model validation by an experiment of sphere sedimentation, the process of pebble recirculated at five constant rates are simulated. The correlations of gas motion and pebble motion in the upper and lower half beds are analyzed to uncover the inter-phase relationships for such intermittent pebble flows. Based on the systematic analyses of the two-phase flows, including the mean field and r.m.s field, the historical variation, inter-correlation, and the spectrum and phase space representations, we found sufficient evidences for the characteristics of intermittency, simultaneity, periodicity, and linear dependence for the inter-phase interaction of gas-pebble flows.

1. Introduction

The core of pebble bed type-high temperature gas-cooled reactor is graphite moderated and helium cooled and can be operated at high temperatures. Therefore the reactor core is composed of a large amount of graphite and fuel pebbles moving in the high temperature helium atmosphere. The pebble is discharged continuously, slowly and intermittently by a silo at the bottom of the pebble bed and recirculated or reloaded at the top of bed simultaneously. The helium gas flows through the void space between the pebble elements takes away the heat generated by the fission of U-235 and then transfers the heat to the steam generator. Therefore, it is a special gas-particle system and many important aspects on the gas-pebble system need to be better explored.

For example, for fuel management, Tavron and Shwageraus (2016) studied the procedure of optimization of pebble bed reactor fuel management, e.g. OTTO (Once-Through-Then-Out) and MEDUL (German: ‘MEhrfach DUrchLauf’ = multi-pass) fuel managements, under the constrained thermal hydraulic conditions. The fuel management performance at equilibrium cycle conditions was evaluated by the VSOP (Very Superior Old Program) code and the pebble bed reactor was found with low sensitivity to fuel management parameters. For pebble flow, Khane et al. (2016) conducted an experimental work on the pebble flow dynamics in a scaled-down pebble bed test reactor using radioactive particle tracking (RPT) technique, including the Lagrangian trajectory, velocity field, residence time distributions. They also assessed the possibility of using pebble bed modular reactor as static packed bed approximation and compared the packing characteristics of static and moving pebble beds (Khane et al., 2017). Our group also performed a numerical study on the bed configuration on the pebble flow, and implied that the brachistochrone shaped bed configuration is the best for flow uniformity (Gui et al., 2014). Moreover, a model study was also conducted to explain the normal distribution of pebble concentrations in the pebble trajectory bundles (Gui et al., 2014). For graphite dust deposition, Jayaraju et al. (2016) dealt with Reynolds averaged Navier-Stokes modeling of fluid flow and graphite dust deposition in pebble bed using the standard $k-\epsilon$ model for the continuum phase and the continuous random walk model for the dispersed phase. After model validation, it was applied to analyze the complex flow behavior and deposition pattern in a structured and an unstructured pebble-bed arrangement. In a similar manner, Barth et al. (2014) presented a positron emission tomography (PET) measurement of dust particle deposition and re-suspension in a fluid dynamically scale HTR pebble

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bed. For heat transfer, Beer et al. (2017) investigated the separate contribution of conductive and radiative heat transfers in packed pebble beds, including the wall effects. Our group also proposed new models, including different length scales (short-range, long-range, and micro-scales) and temperature ranges, for prediction of radiative heat transfers in HTGR (Wu et al., 2016; Wu et al., 2017).

On the gas-particle coupling, Liu et al. (2017) showed a research on the pneumatic transportation pattern of fuel pebbles in the pipes outside the pebble bed core and studied the force condition and dynamic characteristics of two pebbles in the TFPLT (Two Fuel Pebbles Lifted Together) pattern. Abdulmohsin and Al-Dahhan (2016) measured the axial dispersion coefficients, the residence time distributions, experimentally, and found that the pebble size strongly affects axial dispersion and mixing in the packed pebble-bed reactor. Abou-Sena et al. (2014) measured the helium pressure drop across various HCPB-relevant pebble beds. They found that the pressure drop significantly increases with decreasing the pebbles diameter, and the pressure drop is directly proportional to the inlet pressure at the same superficial velocity. Chen et al. (2017) implemented a DEM-CFD simulation study of the pebble bed, including the porosity, velocity and pressure field distributions, as well as the wall effects. The simulation results showed about 11% error different from the pressure drop predicted by the Ergun Equation. Similarly, Zhang et al. (2016) also showed a DEM-CFD simulation of purge gas flow in a DEM-obtained randomly packed pebble bed, where the flow parameters of the purge gas in channels were solved by CFD. They showed that the normalized velocity magnitudes have the same damped oscillating patterns with radial porosity distribution. Moreover, Li and Ji (2015) employed a coupled multi-physics model to account for the fluid-pebble interactions in the dynamics of a large annular nuclear reactor system, and to accurately predict the coolant dynamics and fuel bed mechanical properties. The discrete element method is used to simulate the pebble motion and predict pebble packing density, coordination number and contact stress distributions. The CFD is employed to predict the locally averaged coolant properties and exchange of fluid-pebble interaction forces. In addition, similar DEM-CFD modeling methods have been used for spouted beds (Yang et al., 2015; Yang et al., 2014) and packing beds (Wu et al., 2017; An et al., 2016).

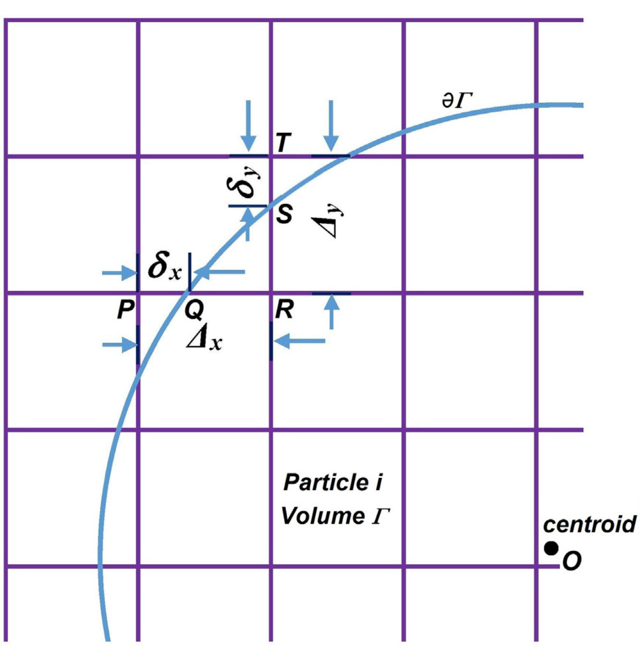

Fig. 1. Sketch of the scheme of IB method.

Note that the real pebble bed reactor is always operating at the re-circulation pattern. Although the DEM-CFD simulation of packed beds have been studied, the pebble motion inside the gas atmospheres under a recirculation mode of fuel pebbles are still poorly understood. More importantly, few works have been performed on the detailed inter-phase coupling in the reactor core. As well known, the lattice Boltzmann method is one of powerful mesoscopic numerical methods for easy parallel computing, and immersed boundary method is an advantageous numerical technique particularly for fine-scale momentum coupling on gas-particle interface. Discrete element method has been widely applied in a variety of engineering applications. Therefore, a hybrid approach, i.e. LBM-IB-DEM coupled method, may be a good choice for fine-scale study of gas-pebble interaction in pebble bed flows. Only a few similar work has been performed recently on two-particle or multiple-particle sedimentation process (Zhang et al., 2014; Zhang et al., 2018). Therefore, a LB-IB-DEM coupled approach is utilized herein, where the gas-phase, gas-pebble momentum interaction, pebble-pebble collision are solved by the lattice-Boltzmann, immersed-boundary, and discrete element method, respectively. The aim of this work is to explore the mode of pebble recirculation on the flow dynamics of pebbles as well as the modulation on gas-phase flows.

2. Methodologies

2.1. Lattice-Boltzmann method

In the quasi-two-dimensional test facility of our laboratory (Yang et al., 2012), the pebbles are recirculated in the air atmosphere. For this apparatus, the gas-phase is the stationary air and herein simulated by the lattice-Boltzmann method (LB), which is consisted of three components, the discrete velocity model, the equilibrium distribution function and the evolution equation. We simply employed a D2G9 model Guo et al. (2002) to simulate the stationary gas atmosphere based on the Boussinesq hypothesis. The discrete velocities in are formulated as follow:

$$\boldsymbol{e}_\alpha = \begin{cases} (0,0), \alpha = 0, \\ (\cos(\alpha-1)\frac{\pi}{2}, \sin(\alpha-1)\frac{\pi}{2})c, \alpha = 1,2,3,4, \\ \sqrt{2}(\cos(2\alpha-1)\frac{\pi}{4}, \sin(2\alpha-1)\frac{\pi}{4})c, \alpha = 5,6,7,8. \end{cases} \tag{1}$$

where $c = \delta x/\delta t = 1$ is the lattice velocity, δx and δt are the mesh spacing and time step, respectively. The density equilibrium function is defined as:

Table 1
Parameters used in simulation and experiment.

Bed dimension $W \times H$, (mm)	800×1000
Angle of inclined plane θ to the horizon, (°)	30
Number of particles N_p	3600
Particle diameter d_p, (mm)	12
Particle density ρ_p, (kg/m^3)	1250
Fluid density ρ_f, (kg/m^3)	0.1786
Fluid viscosity μ_f, (Pa·s)	0.714×10^{-5}
Stiffness factor k_c (N/m)	10^3
Poisson ratio ν	0.3
Restitution coefficient e	0.90
Friction coefficient γ	0.3
Time step δt (s)	10^{-4}
Number of simulation step N_t	5×10^5
Time interval for every particle recirculation T_r, (s)	1, 2, 3, 4, 5 (Case 1–5 respectively)