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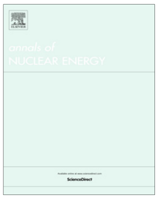

Effect of wall structure on pebble stagnation behavior in pebble bed reactor

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ABSTRACT

Crystallization of pebbles in pebble bed is a crucial problem in high temperature gas-cooled pebble-bed reactors. This phenomenon usually happens along the internal surface and leads to a large number of stagnated pebbles, which poses a threat to reactor safety. In real reactor engineering, wall structures have been utilized to avoid this problem. This article verifies the crystallization phenomenon through DEM (discrete element method) simulation, and explains how wall structures work in preventing crystallization. Moreover, several kinematic parameters have been adopted to evaluate wall structures with different shapes, sizes and intervals. Detailed information shows the impact of wall structure on flow field in pebble bed. Lastly, the preferred characteristics of an effective wall structure are suggested for reactor engineering.

1. Introduction

The high temperature gas-cooled reactor (HTGR) is generally recognized as a promising option for Generation IV advanced reactors. Its advantages, such as extreme safety, modularity, broad applications, and short construction period, have drawn great public attention. The pebble-bed configuration of core has been chosen by many test and demonstration facilities, like HTR-10 in Tsinghua University, China, MPBR in South Africa and the prototype reactor known as AVR in Germany. Pebble-bed reactor is becoming the mainstream technical solution for HTGRs.

Thousands of fuel pebbles, which are loaded from the top and discharged from the bottom, flow through the core under gravity at a very slow velocity (about 10^{-4}–10^{-3} m/h inside the bed), forming the so-called extremely slow granule flow. The mechanism of this special flow regime is poorly understood at present, and many investigations, including experimental (Yang et al., 2012; Jiang et al., 2012; Kadak and Berte, 2001; Kadak and Bazant, 2004) and numerical (Choi et al., 2004, 2005; Li et al., 2009; Shams et al., 2012, 2013a,b,c; Ferng and Lin, 2013), have been carried out to reveal its features. The practical design of HTGRs is indebted to detail studies performed on different complications in pebble bed, like two-region arrangement (Yang et al., 2009), pebble dispersion (Gui et al., 2014a), stagnant region (Li et al., 2013) and optimization of bed configuration (Gui et al., 2014b).

However, wall structures of pebble bed have not been given enough emphasis yet. In the pebble-bed reactor HTR-10 built by INET, Tsinghua University, wall structures have been adopted, as shown in Fig. 1. These structures can give an obvious effect to the overall flow field through influencing pebble motions in the near-wall region. Specifically, with help of the unsmooth internal surface, blocking or crystallization of pebble flow that often happens along the wall would be eliminated to some extent. This definitely contributes to the elimination of stagnant region and improves reactor's safety capacity by reducing probability of radiation leakage. Moreover, such structures enhance the dispersion of pebbles in the peripheral core, so that these fuel pebbles are more likely to move to relatively central region and be exposed to more neutron flux, which would narrow the burnup level in radial direction.

This article aims to present the effect of wall structures upon pebble flow and to propose the best configuration of wall structure for practical engineering. This study is carried out through numerical simulations by employing discrete element method (DEM) embedded in the open source CFD platform-OpenFoam.

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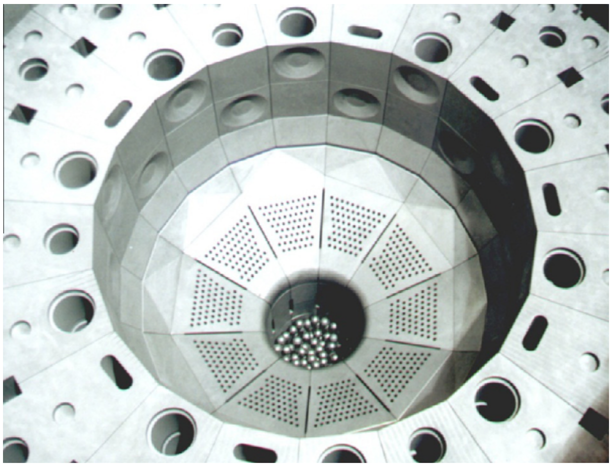

Fig. 1. Internal wall of HTR-10 in INET, Tsinghua University.

2. Numerical description

2.1. Discrete element method (DEM)

In discrete element method (DEM), the particles are discretized to a collection of unique "discrete elements". Each particle is traced deterministically by the Newton's law of motion and interaction between particles is governed by contact models. In general, the governing equations of each particle can be depicted as follows:

$$m_i \frac{dV_i}{dt} = \sum_{j=1}^{n} F_{ji}^C + F_i^e + F_i^g \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n} r_{ij} \times F_{ji}^C + M_i^e \tag{2}$$

where m_i, I_i, V_i and ω_i are the mass, moment of inertia, translational and rotational velocities of element 'i', respectively. F_{ji}^C is the contact force from element 'j' to 'i'. F_i^e and M_i^e are respectively the force and moment from the environment (not considered here). F_i^g is the gravity force and r_{ij} is the vector pointing from element 'i' to 'j'.

The contact force F_{ji}^C can be decomposed into two parts: the normal contact force F_{ji}^{cn} and the tangential force F_{ji}^{ct}, which are given as follows:

$$F_{ji}^{cn} = -k_n \cdot \Delta u_{ij}^n + \beta_n \cdot V_{ji}^n \tag{3}$$

$$F_{ji}^{ct} = -k_t \cdot \Delta u_{ij}^t + \beta_t \cdot V_{ji}^t \tag{4}$$

$$|F_{ji}^{ct}|_{\max} \leqslant \mu |F_{ji}^{cn}| \tag{5}$$

where k and β represent the stiffness and damping coefficients; μ is the friction coefficient; Δu_{ij} represents the deformation, and V_{ji} represents the relative velocity of two contacting particles. 'n' and 't' denote the normal and tangential components respectively. Based on the Hertz contact theory, these parameters are expressed as follows:

$$k_n = \frac{\pi^2}{R^2} \cdot \frac{E(1-\nu)m_{ij}}{\rho(1+\nu)(1-2\nu)} \tag{6}$$

$$k_s = \frac{(1-2\nu)}{2(1-\nu)} \cdot k_n \tag{7}$$

$$\beta_n = -\frac{2\ln e}{\sqrt{\pi^2 + \ln^2 e}} \cdot \sqrt{k_n m_{ij}} \tag{8}$$

$$\beta_s = -\sqrt{\frac{8}{5} k_s m_{ij}} \tag{9}$$

where E, ν, R, ρ, e are elastic modulus, Poisson ratio, pebble radius, density and restitution coefficient respectively. $m_{ij} = m_i m_j/(m_i + m_j)$ is the reduced mass.

2.2. OpenFoam and simulation setup

OpenFoam is employed to numerically investigate the circulating pebble bed. OpenFoam is an open source CFD platform which offers a variety of standard solvers for different situations. Its principal advantage over other commercial software is that users and researchers are free to look up the source code and modify standard solvers according to their specific requirements. One of those provided solvers called "icoUncoupledKinematicParcelFoam" is adopted as the foundation of DEM simulation. Additionally, several necessary modifications have been made upon this standard solver to fit the practical running pebble bed.

The geometry of normal pebble bed is depicted in Fig. 2. A bed with 800 mm × 1200 mm × 12.5 mm in width, height, and depth directions, respectively, has a 120 mm wide drainage orifice at the bottom center. 4224 pebbles with equal diameter of 12 mm are loaded into the bed to create the initial packing state. When circulation starts, the discharging rate of pebbles is set to match the loading rate, so that the total number of pebbles in the bed remain constant, namely 4224. Two recirculation rates of 20 and 40 pebbles per second are used in our simulations to present two operating modes. Detailed information about the simulation is listed in Table 1.

Note that the depth of the bed is just a little larger than the diameter of pebbles, which only allows one layer of pebbles to flow through the bed. This kind of bed can be treated as a slice of real cylindrical pebble bed that crosses the axis. This three-dimensional section of the pebble bed could demonstrate the influence of wall structures on pebble flow field. The study of a whole three-dimensional geometry – by increasing the depth of current geometry – could be direction for future work.

For the sake of comparison, different wall structures have been taken into account in this study. The aim of this study is to optimize the HTGR design by adopting the most proper wall structure in terms of shape, size and interval pitch. Dimension parameters of wall structures can be looked up in Table 2. All of the three kinds of wall structures can help disturbing the "boundary layer" of pebble flow, intensifying pebble dispersion and eliminating crystallization in the near-wall region.

3. Simulation results and discussion

3.1. Wall structure effect

It is necessary to illustrate the difference between pebble beds with and without wall structures from the perspective of graphical analysis. Identical conditions, except configuration of wall (as shown in Fig. 2), are set in simulations to highlight the influence of wall structures.

4224 pebbles are loaded into bed at the beginning of simulation, and it takes them about 0.3 s to form the random packing state under the gravity. The forming process is shown in Fig. 3. Then, circulating mode starts, and it lasts for 300 s with the circulating rate of 20 pebbles per second. The total number of pebbles within bed remains constant throughout the simulation.

The burn-up level is directly impacted by the age of the fuel pebbles in practical reactors. Aged fuel pebbles stay in the core for a long time; this might damage pebbles and lead to radiation leakage. Specifically, in our simulations, age of a pebble is defined