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# Effect of bed configuration on pebble flow uniformity and stagnation in the pebble bed reactor

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## HIGHLIGHTS

- Pebble flow uniformity and stagnation characteristics are very important for HTR-PM.
- Arc- and brachistochrone-shaped configuration effects are studied by DEM simulation.
- Best bed configurations with uniform flow and no stagnated pebbles are suggested.
- Detailed quantified characteristics of bed configuration effects are shown for explanation.

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## ABSTRACT

Pebble flow uniformity and stagnation characteristics are very important for the design of pebble bed high temperature gas-cooled reactor. Pebble flows inside some specifically designed contraction configurations of pebble bed are studied by discrete element method. The results show the characteristics of stagnation rates, recycling rates, radial distribution of pebble velocity and residence time. It is demonstrated clearly that the bed with a brachistochrone-shaped configuration achieves optimum levels of flow uniformity and recycling rate concentration, and almost no pebbles are stagnated in the bed. Moreover, the optimum choice among the arc-shaped bed configurations is demonstrated too. Detailed information shows the quantified characteristics of bed configuration effects on flow uniformity. In addition, a good design of the pebble bed configuration is suggested.



## 1. Introduction

The uranium-based, graphite-moderated, helium-cooled pebble bed type – high temperature reactor is considered as the promising generation IV advanced nuclear reactor, for its high efficiency, attractive economics, and high levels of passive safety (Jiang et al., 2012). HTR-PM was approved as one of the national special grand science-technology projects of China (Zhang et al., 2004). A demonstration reactor, i.e. the 10 MW high temperature reactor, named HTR-10 shortly, was developed by the INET at Tsinghua University, which is among the few test reactors of high temperature reactor over the world, such as AVR in Germany (Schulten, 1978), PBMR in South Africa (Koster et al., 2003), MPBR in USA (Kadak & Berte, 2001), and etc.

In the reactor core of HTR-PM, the pebbles are flowing very slowly driven only by gravity, termed as a quasi-static flow regime. They are discharged from the drainage orifice at the bottom, and reloaded at the top of the reactor core, forming a recirculation mode of operation. In this recirculation process, the velocities of pebbles throughout the bed are varied greatly, depending on the bed configurations, friction coefficients, discharging and reloading approaches, and etc. In general, pebbles move rapidly in the central region and slowly near the wall or around the corners of the bed. The uniformity of pebble flow and distribution of residence time (relevant to stagnated pebbles) are of crucial importance for the performance and safety of reactor operation, which should be taken into account carefully in reactor core design work.

Due to the cone-type contraction at the bottom of pebble bed, the pebbles in the stagnant region around the corner move extremely slowly or even stay at rest. For example, the number rate of drainage of pebbles in the HTR-10 demonstration reactor at Tsinghua University is about 100/day. Under such a low flow rate, the order of mean velocity is only about $O(10^{-4})$ m/h inside the bed and about $O(10^{-3})$ m/h inside the drainage orifice. In another experiment facility, it is speeded up to 150/min (Yang et al., 2012), with the order of velocities of about $O(10^{-3})$ m/min. Both of them are extremely slow pebble flows which are almost quasi-static flows. On the other hand, the stagnated pebbles are not allowed in real

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reactors since the residence time of the stagnated fuel pebbles can go beyond the burn-up level. Excessive stay time could result in severe irradiation and thermal damage to fuel pebbles with possible fission product escaping, which certainly increases the risk of leakage of radiation (Li et al., 2013). Thus, the formation of stagnant region is one of the critical issues in the pebble bed reactor design.

Lots of studies of pebble flows or similar granular flows have been carried out in the past decades, contributing to various related aspects of them, such as velocity profiles (Choi et al., 2005; Kim et al., 2013), phenomenological analysis (Yang et al., 2012), two-region design (Jiang et al., 2012), diffusion and mixing (Choi et al., 2004), as well as numerical simulations (Li et al., 2009; Shams et al., 2012, 2013a,b,c; Ferng and Lin, 2013) and detailed analysis (Rycroft et al., 2006), etc. However, few of them have focused on the effect of bed configuration, especially the contraction configuration at the bottom of bed, on flow uniformity and pebble stagnation characteristics. Noticed and motivated by the significance of this issue, this study aims to show and demonstrate some typical results on the bed configuration effect. To accomplish this, some basic shapes are used for the configuration of bed contraction, and the discrete element method is employed to simulate the pebble flows in these specific designed bed configurations.

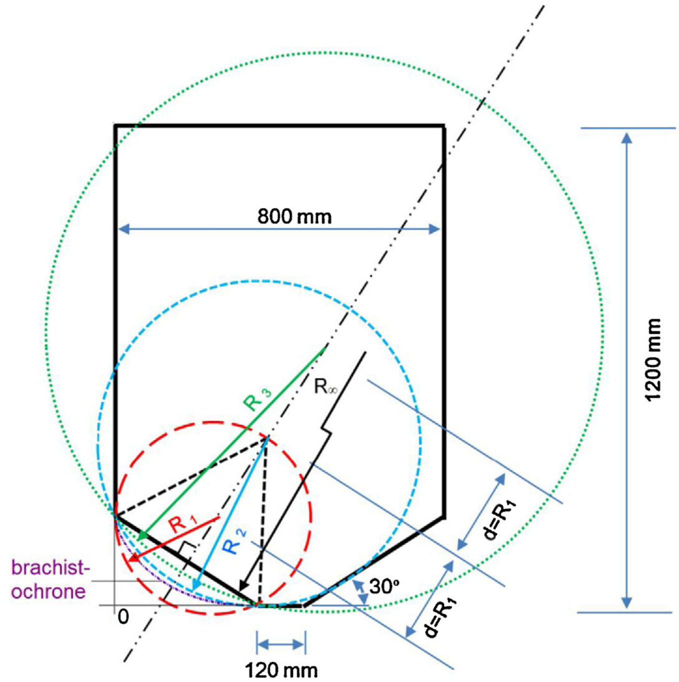

**Fig. 1.** Sketch of bed configuration.

## 2. Numerical description

### 2.1. Discrete element method

The fundamental principle of discrete element method (DEM) is that the particle assembly is discretized into discrete elements, with each one traced deterministically by the Newton's law of motion and the interactions between each other governed by some basic mechanical models. In general, the governing equations of each particle can be described as follows:

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

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

where $m_i$, $I_i$, $V_i$ and $\omega_i$ are the mass, moment of inertia, translational and rotational velocities of particle '$i$', respectively. $F_{ji}^{C}$ is the contact force from element '$j$' to '$i$'. $F_i^{g}$ is the gravity force. $r_{ij}$ is the position vector pointing from element '$i$' to '$j$'.

Then, the contact force $F_{ji}^{C}$ can be decomposed into the normal and tangential components, formulated respectively as below:

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

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

$$|F_{ji}^{ct}|_{\max} \le \gamma |F_{ji}^{cn}| \tag{5}$$

where $k$ and $\beta$ represent the stiffness and damping coefficient, respectively. $\gamma$ is the friction coefficient. $\Delta x_{ij}$ and $V_{ji}$ represent the deformation and relative velocity respectively. '$n$' 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 $E$, $\nu$, $R$, $\rho$, $e$ 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. Simulation setup and bed configuration

The simulation setup is sketched in Fig. 1. A bed with 800 mm × 1200 mm × 12 mm in width, height, and depth directions respectively has a 120 mm wide drainage orifice at the bottom center. About 7345 pebbles with equal diameters of 12 mm are loaded into the bed uniformly at the bed top and drained from the drainage orifice at a fixed drainage rate (100 pebbles per second) which is the same of the reloading rate. The properties and dimension parameters are listed in Table 1.

It is noticed that the depth of the bed is equal to the diameter of the pebbles. It is because the present model is a three-dimensional model which has already been validated and utilized in previous studies, such as particle flow study in drum (e.g. Gui et al., 2010, 2013, etc.) and phenomenological study in pebble bed (Yang et al.,

**Table 1**
Parameters used in simulation.

| | |
|---|---|
| Dimension of pebble bed $D_x \times D_y \times D_y$ (mm) | 800 × 1200 × 12 |
| Diameter of outlet $D_{out}$ (mm) | 120 |
| Base cone angle $\alpha$ (°) | 30 |
| Pebble diameter $d_p$ (mm) | 12 |
| Pebble number $N_p$ | 7345 |
| Friction coefficient $\gamma$ | 0.3 |
| Restitution coefficient $e$ | 0.95 |
| Stiffness factor $K_n$ (N m$^{-1}$) | $1 \times 10^4$ |
| Poisson rate | 0.3 |
| Time step (s) | $1 \times 10^{-4}$ |
| Total simulated time (s) | 150 |
| Drainage rate of pebbles (s$^{-1}$) | 100 |