Advanced Powder Technology 28 (2017) 499–505

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

# Three-dimensional numerical simulation of quasi-static pebble flow

X.M. Sun [a], Y.J. Dong [a], P.F. Hao [b,*], L. Shi [a], F. Li [a], Y.T. Feng [c]

[a] Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China
[b] School of Aerospace, Tsinghua University, Beijing 100084, China
[c] Zienkiewicz Centre for Computational Engineering, Swansea University, Swansea SA1 8EN, UK

ARTICLE INFO

*Article history:*
Received 23 April 2016
Received in revised form 31 October 2016
Accepted 15 November 2016
Available online 24 November 2016

*Keywords:*
Pebble flow
Granular flow
Discrete element method
Sphere packing
Pebble bed

ABSTRACT

To investigate the influence of the drainage rate and the particle contact model on the main features of the pebble flow, a quasi-static pebble flow of full scale German HTR-MODUL pebble bed is performed with up to 360,000 frictional graphite spheres. The treatment of the sphere-wall boundary condition is analyzed to avoid underestimating the friction of pebble near the wall. The streamlines, diffusion of pebbles and velocity profiles of pebble flow are drawn and analyzed. It shows that the streamlines and diffusion of pebbles inside the pebble bed are barely affected by the drainage rate and the particle contact model used. However, it reveals that the drainage rate and the contact model obviously influence the pattern of velocity profiles. It demonstrates that the quasi-static pebble flow and the Hertzian model are optimal choices of the neutronic physical design of the pebble bed reactor when the residue time of pebbles is particularly concerned.

## 1. Introduction

As one of the main candidates for the next generation of nuclear power plants [1], the advantages of the pebble bed type high temperature reactor (HTR) include online refueling, passive safety features, and a high coolant outlet temperature. Besides more efficient electricity production, these features also have numerous applications for process heating and hydrogen production. The pebble bed reactor uses spherical graphite pebbles as fuel elements. In a pebble bed reactor, fuel pebbles form a randomly stacked bed inside a graphite reflector through which the helium coolant is pumped. The fuel pebbles circulate very slowly during the reactor operation.

The behavior of fuel pebble flow within a pebble bed reactor is an important issue. The streamline pattern of pebble flow and the diffusion of pebbles determine the design of refueling, and the velocity profile of pebble determines the residue time of pebble in the reactor, which are key factors of the reactor physical design. A vast amount of research has been carried out in order to accurately model pebble packing in a reactor core for the purpose of neutronic analysis, including the computation of the burnup distribution [2,3], the effective thermal conductivity [4], the dust production [5], and the flow and thermal field coupling [6–8].

Over the past few decades, pebble circulation has been modeled as a dense quasi-static granular flow driven by the gravity. Although the kinematic model [9] and the microscopic model for random-packing dynamics has been proposed [10,11], there is no reliable continuum model to predict the mean velocity in silos of different shapes [12]. Recently, much effort has been made to obtain realistic pebble flow features by the high fidelity Discrete Element Method (DEM) [13–17]. In recent years, small scale pebble bed simulations have been carried out with less than 30,000 pebbles [15–17]. However, the influences of boundary constrains for small scale problems are quite different from large scale ones.

Cogliati and Ougouag [18,19] developed the PEBBLES code for modeling pebble flow for a large scale PBMR reactor. PEBBLES adopts a Hookean model as the particle contact model. However, the number of pebbles and the pebble drainage rate involved in computation are not quite clear.

The first known large scale pebble flow simulation by DEM code is shown by Rycroft et al. [20,21], with up to 440,000 frictional, viscoelastic 6 cm-diameter spheres draining in a cylindrical vessel with a diameter of 3.5 m and a height of 10 m. In Rycroft's work, the streamline and velocity profiles are obtained, and the diffusion and mixing of pebbles are analyzed. For the reason of infeasible data collection, the Hookean model is adopted, the drainage of pebbles is not controlled on purpose, and the rate of removing pebbles is much faster than it is in the reactor core. In addition, the numerical

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* Corresponding author.
*E-mail address:* haopf@tsinghua.edu.cn (P.F. Hao).

http://dx.doi.org/10.1016/j.apt.2016.11.007

simulation timestep of DEM has to scale according to $K_n^{-1/2}$ where $K_n$ is the normal stiffness of the pebbles, otherwise the computation goes divergent and fails. Therefore, a realistic stiffness coefficient definitely leads to a much lower timestep. For computational feasibility, Rycroft uses a physically unrealistic value of normal stiffness which is significantly softer than that of typical fuel pebbles in pebble bed reactors. As a comparison, in this work, a physically realistic stiffness coefficient is used.

With all of these great works, there are still some uncertainties yet to be cleared. Such as, how do drainage rate and particle contact models influence the main features of the pebble flow, such as streamline pattern, diffusion of pebbles and velocity profile? In fact, the pebble flow in HTR is so slow that the original disturbance caused by the removal process of the pebbles is completely decayed before the next takes place [22]. Although the previous experimental work by Choi et al. [12,23] has shown that the main features of the flow are predominately governed by geometry and packing constraints, the influence of the drainage rate on the main features of the pebble flow is still not quite clear. Besides the issue of drainage rate, the Hookean model is often adopted by most DEM code for the sake of computational feasibility despite its unrealistic linear spring hypothesis. Thus there is a demand to do the comparison of the influences of the Hookean model and the Hertzian model on the main features of the pebble flow.

The main aim of this work is to investigate the influence of the drainage rate and the particle contact model on the main features of the pebble flow. For this purpose, the DEM code with both Hookean and Hertzian models is implemented in C/C++ language and optimized to run in parallel. The quasi-static pebble flow of a full scale German HTR-MODUL pebble bed is performed with up to 360,000 frictional graphite spheres draining in a cylindrical vessel of diameter 3 m and height 9 m.

## 2. Method

### 2.1. DEM method

DEM is based on the concept that individual material elements are considered to be separate and contacted only along their boundaries by appropriate physically based interaction laws. The interaction of forces between each contact pair are determined according to a constitutive relationship or interaction law. Based on Newton's 2nd law, the dynamic equation for pebble *i* is

$$\mathrm{m}\boldsymbol{a}_i = \sum_j \boldsymbol{F}_{ij}^c + m\boldsymbol{g} + \boldsymbol{F}_i^e, \tag{1}$$

where $m$ is the mass of the pebble; $\boldsymbol{a}_i$ is the translational acceleration; $\boldsymbol{F}_{ij}^c$ is the contact force between pebbles $i$ and $j$; $F_i^e$ is the resultant of all externally applied forces that could also include forces from the pebble interaction with other phases not explicitly modeled, such as fluid flows and electric/magnetic fields. In the current work being conducted, no such external forces, except for gravity, are considered. Also note that, during the static packing generation and even the subsequent recycling of the fuel spheres, the motion of the spheres is quasi-static at the most, the rotational motion is negligible, and therefore the rotational motion is ignored to reduce computational costs and improve simulation performance.

The contact force between a pebble $i$ and another pebble is represented by $F_i$,

$$\boldsymbol{F}_i = F_n\boldsymbol{n}_i + F_t\boldsymbol{t}_i, \tag{2}$$

where $F_n\boldsymbol{n}_i$ is the normal contact force with $\boldsymbol{n}_i$ being the unit normal direction vector and $F_n$ being the magnitude; while $F_t\boldsymbol{t}_i$ is the tangential force with $\boldsymbol{t}_i$ being the tangential direction unit vector and $F_t$ being the magnitude. As shown in [20],

$$\boldsymbol{F_n} = \boldsymbol{f}\left(\frac{\delta}{d}\right)\left(-\boldsymbol{k_n}\delta - \frac{\gamma_n v_n}{2}\right), \tag{3}$$

$$\boldsymbol{F_t} = \boldsymbol{f}\left(\frac{\delta}{d}\right)\left(-\boldsymbol{k_t s_t} - \frac{\gamma_t v_t}{2}\right), \tag{4}$$

where $\delta$ is the normal overlap, $d$ is the diameter of pebble, $\gamma_n$ and $\gamma_t$ are the elastic and viscoelastic constants, $v_n$ and $v_t$ are the normal and tangential components of the relative surface velocity. $s_t$ is the elastic tangential displacement between spheres. The function $f$ is customized for different contact model. The Hookean model employs $f(\xi) = 1$, while the Hertzian model uses $f(\xi) = \sqrt{g(\xi)}$ [24,25].

The selection of a set of contact laws to be used for a particular application should be mainly based on the physical phenomena involved. In this work, the classic Hertzian contact model that governs elastic contact of two equal sized spheres in small strain deformation is adopted as the normal contact model. The tangential, or frictional, force between two contacting spheres is described by a tangential contact model in DEM. There are a few different models available to be considered. The Hertz-Mindlin-Deresiewicz model [26–29], which takes into account the interactions between the normal and tangential (frictional) forces and is regarded as the most accurate model, has been adopted as the tangential contact model.

In this work a physically realistic stiffness coefficient is used which is much higher than it is in Rycroft's work [20,21]. Since the simulation timestep of DEM must scale according to $K_n^{-1/2}$ where $K_n$ is the normal stiffness, the simulation timestep is much smaller in this work and it takes much more CPU time to perform the simulation. The computations are carried out on 8 Dell servers with 16-core 3.5 GHz Intel processors, and it takes more than half a year to obtain the results.

### 2.2. Wall boundary

With regard to the sphere-wall boundary treatment, there is a prevalent method called the GHOST PEBBLE which seemingly comes from Computational Fluid Dynamics (CFD). As shown in Fig. 1, to compute the contact force between a sphere and the wall, a GHOST PEBBLE is in a mirrored place along the wall. In this way, the formula of sphere-sphere can be applied at first glance. However, the following analysis reveals the drawback of the GHOST PEBBLE method.

For a given normal overlap $\delta_n$, the magnitude of the normal contact force between spheres, $F_n$, is given by

$$F_n = \frac{4E^*}{3}\sqrt{R^*}\delta_n^{3/2} = K_n\delta_n, \tag{5}$$

with the "secant" normal stiffness $K_n$ defined as

$$K_n = \frac{4E^*}{3}\sqrt{R^*\delta_n}, \tag{6}$$

where $E^*$ and $R^*$ are, respectively, the equivalent Young modulus and radius of the two spheres. In the current case, all the spheres have the same radius and material properties, and thus

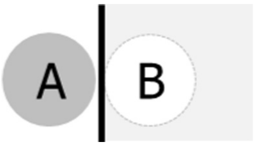

**Fig. 1.** Sphere A is a pebble near the wall and sphere B is the corresponding ghost pebble.