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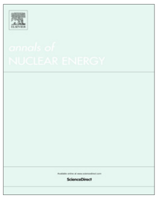

Modeling stationary and moving pebbles in a pebble bed reactor

Xiang Zhao [a], Trent Montgomery [a], Sijun Zhang [b,*]

[a] College of Engineering, Technology and Physical Sciences, Alabama A&M University, 4900 Meridian Street, Huntsville, AL 35762, USA
[b] ESI CFD, Inc., 6767 Old Madison Pike, STE 600, Huntsville, AL 35806, USA

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ABSTRACT

This paper presents a numerical study of the stationary and moving pebbles in a pebble bed reactor (PBR) by means of discrete element method (DEM). The packing structure of stationary pebbles is simulated by a filling process that terminates with the settling of the pebbles into a PBR. The packing structural properties are obtained and analyzed. Subsequently, when the outlet of the PBR is opened during the operation of the PBR, the stationary pebbles start to flow downward and are removed at the bottom of the PBR. The dynamic behavior of pebbles is predicted and discussed. Our results indicate the DEM can offer both macroscopic and microscopic information for PBR design calculations and safety assessment.

1. Introduction

To address the long-term challenge of global climate change, the development of reliable, clean, safe and affordable energy resources has gained more attention and renewed interest all over the world. As the only large-scale emission-free energy resources, nuclear power is considered to be a promising option and becomes even more attractive as the re-introduction of pebble bed reactor (PBR) to this field. PBR uses pyrolytic graphite pebbles as the neutron moderator, and an inert gas such as helium as the coolant. The helium gas is heated to a very high temperature in the PBR and used to drive a turbine to generate electricity. Compared with the traditional light water reactor, the PBR has lower risk and higher thermal efficiency. In a PBR, the pebbles are randomly packed in a cylindrical vessel. Thorough knowledge of packing structures is essential to improve the thermal efficiency and assess the safety.

In general, a PBR has a central core comprised entirely of reflector graphite pebbles, the central core is surrounded by a larger annulus of entirely fuel pebbles. Pebbles are dropped into the top of the core and are allowed to freely fall onto the pebble pile. The graphite pebbles are dropped only in the center while the fuel pebbles are dropped on the periphery. The pebbles are drained out through the bottom and reinserted at the top. The positions of the pebbles are determined entirely by granular flow, and random dropping from the top of the core. In a PBR, pebbles enter at the top of the reactor vessel, pass through the bed and then out through the base of the vessel via an extractor. Of special importance is the information about pebble pathway and relative velocity through the bed. This information is crucial since excessive time spent in parts of the bed could result in severe irradiation and thermal damage to the pebble with possible escape of fission products. An extreme case would be the permanent fixation of a given pebble or group of pebbles in a region of the vessel. The feasibility of the recycling of pebbles in a PBR depends on the maintenance of satisfactory pebble flow through the vessel, its outlet, and the pebble extractor. Therefore, accurate flow characterization and description of the dynamics of pebbles in a PBR is important with respect to the basic reactor design calculations, optimization of fuel cycle and burn-up calculations, and monitoring of fuel integrity over its lifetime.

Obviously, understanding the packing structures and flow patterns of pebbles in a PBR is needed for design optimization and safety assessment. In the past, significant efforts have been made to mathematically determine the packing structure of particles and numerically describe the dynamics of flowing particles. Generally speaking, those methods can be classified into two types: macroscopic and microscopic length scales. As a consequence, for the packing of mono-sized spheres, structural properties such as packing density, radial distribution function, and coordination number distribution, etc have well established for general applications in terms of macroscopic concept. Simulation algorithms with only geometrical considerations thus far suffer from a serious drawback, namely, poor accuracy, since they cannot explicitly take any force into account. This deficiency can be overcome by means of the so-called discrete element method (DEM) proposed by

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* Corresponding author. Tel.: +1 256 713 4729; fax: +1 256 713 4799.
E-mail address: sijun.zhang@esi-group.com (S.J. Zhang).

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Nomenclature

d	particle diameter
$\mathbf{f}_{\mathrm{f,i}}$	fluid drag force
$\mathbf{f}_{\mathrm{ij}}$	inter-particle force
$\mathbf{g}$	gravity
I_i	moment of inertia
k_i	number of contacting particles
m_i	mass
t	time
$\mathbf{T}_{ij}$	torque from particle
$\mathbf{v}_{\mathrm{i}}$	translational velocity
Greek letters	
$\boldsymbol{\omega}_{\mathrm{i}}$	rotational velocity
Subscripts	
i	particle index
j	contacting particle index

Cundall and Strack in 1979. The method, sometimes referred to as granular dynamics simulation, in contrast to the molecular dynamics simulation, has been widely used in the study of solid–solid and/or gas–solid interaction in dynamic systems. On the other hand, the behavior of pebbles in a PBR exactly falls into the category of granular materials, as widely recognized in both scientific and industrial communities.

Granular material can be described by a continuum approach stemmed from spatial local average theorem. In the continuum description, the macroscopic behavior of granular flow is described by the conservation equations facilitated with constitutive relations and boundary conditions. In the past, two continuum models developed within the framework of plasticity theory and kinetic theory of molecular dynamics have extensively been used to study the dynamic behavior of granular materials. They have been shown to be applicable to quasi-static and rapid flow regimes, respectively. However, they do not satisfactorily apply to a system in which different flow regimes coexist such as the granular flow in a PBR/hopper. An alternative approach is DEM, which takes into account the distinct nature of granular materials without any global assumptions, thus allowing a better understanding of the fundamental mechanisms of granular flow. To date, the pebble flows in PBRs are poorly understood and not easily accessible through experiments, despite their impact on reactor physics. Recently, Zhao et al. (2009) performed a study on the pebble flow in a rectangular model PBR using DEM approach. In this work, which used a real PBR geometry, DEM was employed to numerically simulate pebble dynamics in a cylindrical PBR.

2. Hopper flows

Hoppers are widely employed in engineering practice mainly due to their capacity to enhance flow conditions for granular materials. They must be properly designed for reliable control. Therefore, a comprehensive understanding of the dynamic behavior of the granular flow in a hopper, so called hopper flow, is essential. In addition, theoretical treatment of granular flow in hoppers provides a class of benchmark boundary value problems for analyzing and predicting the behavior of granular materials under external mechanical excitations. The relatively simple geometry and well-defined flow patterns, despite complicated flow characteristics, have made the hopper flow an attractive case to study new research techniques for granular flows. For these reasons, the granular flows in hoppers has been an important topic of research worldwide for several decades. Especially, in recent years, the dynamics of the flow has been studied extensively by means of both experimental techniques and numerical simulations at a microscopic or particle scale. Such studies take into account the discrete nature of granular materials without requiring any global assumptions that were needed in the previous macroscopic approaches and thus allows a better understanding of the underlying mechanism. DEM is again the most important simulation approach for this connection.

Granular flows in hoppers with various geometries have been studied. These studies are mainly focused on three aspects: wall stress/pressure, discharge rate and internal properties. The study of the bulk material pressure on the walls of a hopper is very important for the hopper design. It has extensively been investigated by means of analytical, experimental and numerical approaches. However, the fundamentals about the pressure are not comprehensively understood due to its dependence on many parameters such as the geometry of hopper, material properties of hopper and particles, and flow conditions. DEM studies can enhance the understanding. The wall pressures along the silo height obtained by discrete element simulations agree well with the results from finite element simulations, analytical approaches or experiments (Langston et al., 1995a; Negi et al., 1997; Holst et al., 1999a,b; Rotter et al., 1998; Masson and Martinez, 2000a,b; Goda and Ebert, 2005). Furthermore, it has also been reported that the wall pressure is affected by particle shape (Cleary and Sawley, 2002) and air-assisted flow which leads to increased wall stresses (Langston et al., 1996). The wall pressure is also affected by inserts whose presence influences the force transmission patterns within a hopper, producing strong and localized loads on the walls and the inserts (Paris et al., 2004).

The prediction of the particle discharge rate from the hopper is of importance for the effective operation and control of a transport system, and is difficult due to the complexity associated with granular flow such as inhomogeneous particle distribution, irregular velocity profile and diverse particle size and shape (Seville et al., 1997). Although various empirical formulations have been proposed, a complete description of discharge rate is still lacking due to its complexity. DEM simulations have been conducted to address this problem. It has been reported that the hopper discharge rate obtained by DEM is qualitatively in good agreement with the results obtained from experiments (Favier et al., 2001) and the empirical predictions (Langston et al., 1994, 1995a; Kano et al., 1998). The discharge rate is affected by particle characteristics and material properties. DEM simulations can quantify these effects. It has been shown that compared with spherical particles, the disc flow is about 20–30% faster (Li et al., 2004); the discs with aspect ratio 5 are discharged 40% faster than the spheres (Langston et al., 2004) and elongated particles produce flow rates up to 30% lower than for circular particles (Cleary and Sawley, 2002). DEM simulations also show that the discharge rate is not so sensitive to the stiffness of particles, wall roughness and damping coefficient, but is affected by particle friction (Langston et al., 1994, 1995a; Kano et al., 1998). Other properties such as hopper geometry and operation also affect the discharge rate. For example, the discharge rate largely depends on the hopper orifice and half-angle (Langston et al., 1994, 1995a; Kano et al., 1998). The ratio of the discharge rates from a vibrating hopper to a non-vibrating hopper decreases with vibration except at the highest frequencies (Wassgren et al., 2002).

It is important to understand the microscopic structure and its relations to the mechanisms governing the hopper flow. The DEM