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Granular flow in pebble-bed nuclear reactors: Scaling, dust generation, and stress

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HIGHLIGHTS

- The scaling properties of granular flow in pebble-bed reactors have been analyzed.
- Simulations in a full-size reactor are compared to those scaled down by 3:1 and 6:1.
- For some features, the scaled-down behavior is complex due to pebble packing effects.
- Pebble stresses and dust generation due to pebble wear are analyzed in detail.
- Approximate scaling laws for pebble stress and wear are developed.

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ABSTRACT

In experimental prototypes of pebble-bed reactors, significant quantities of graphite dust have been observed due to rubbing between pebbles as they flow through the core. At the typical operating conditions in these reactors, which feature high temperatures, pressures, and a helium atmosphere, limited data is available on the frictional properties of the pebble surfaces, and as a result, a conceptual design of a scaled-down version of a pebble-bed reactor has been proposed to investigate this issue in detail. However, this raises general questions about how the granular flow in a scaled facility will emulate that in a full-size reactor. To address this, simulations of granular flow in pebble-bed reactors using the discrete-element method (DEM) have been carried out in a full-size geometry (using 440,000 pebbles) and compared to those in geometries scaled down by factors of 3:1 and 6:1. Differences in velocity profiles, pebble ordering, pebble wear, and stresses are examined, and the effect of friction is discussed. The results show complex behavior due to discrete pebble packing effects, although several simple scaling rules can be derived.

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1. Introduction

Pebble-bed nuclear reactors are a type of gas-cooled high temperature reactor (HTR) that are currently under study as part of the Generation IV initiative, and offer many potential advantages over current reactor technology, such as passive safety, continuous refueling, and proliferation resistance. However, early prototypes have identified a number of potential safety concerns, such as the generation of large amounts of graphite dust as the pebbles flow past each other and against the moderator. During the reactor operation, the dust may become activated, and may accumulate both in the reactor core and the heat exchange system. The characteristics and amount of the generated dust are not well-known, nor is its potential for release during a fast flow velocity increase.

Currently the most extensive data on dust generation is available from the German prototype Arbeitsgemeinschaft Versuchreaktor (AVR) (Gottaut and Krüger, 1990; Kissane, 2009). During the reactor's twenty-year operation span, it is estimated that 50 kg to 60 kg of dust was generated, and the median diameter of the dust particles was 1 μm. The concentration of the dust circulating the reactor was only a very small fraction (10^{-7}) of the total. It is expected that oil and air ingress incidents during the early operation may be responsible for the significant portion of the dust. Furthermore, several different types of fuels were employed over the reactor's lifetime, with the earlier fuel designs being less durable than those

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used later. The relevance of this data to modern reactor designs and graphites is therefore limited.

Recently, a number of research groups have carried out studies that are relevant to the dust generation problem. One significant issue is that the frictional and wearing properties of graphite are not well-known at the typical helium atmosphere, temperatures, and pressures within the reactor, and several experimental studies have aimed to properly characterize these (Brendlé and Stempflé, 2003; Sheng et al., 2003; Luo et al., 2005). Two recent survey articles on frictional properties (Luo et al., 2010) and wear (Cogliati et al., 2011) summarize the available values in the literature. Building on this work, a finite-element analysis of individual pebble interactions has been constructed to more accurately characterize the dust produced during a pebble–pebble contact (Rostamian et al., 2012). In other work, computational fluid dynamics (CFD) simulations of gas flow around pebble assemblies have been conducted (Lee et al., 2007; Hassan, 2008; Wu et al., 2010), which may have important consequences for dust transport. Another recent study has examined the consequences of dust generation for the reactor system as a whole (Stempniewicz et al., 2012).

To complement this work a conceptual design of a experimental facility has been proposed (Lind et al., 2010) that would enable the generation of dust to be studied in a holistic manner. The facility would consist of a core simulator coupled to a heat exchanger. In tandem with analytical work, the project would characterize the aerodynamics of the core and heat exchanger, investigate the amount of dust generated and the locations most prone for deposition, and examine both normal operating conditions as well as fast depressurization events. Due to cost constraints, the experimental facility would be a scaled-down version of a full-size reactor. A suitable full-size reference design is the pebble-bed modular reactor (PBMR) (Kadak, 2007), which features a cylindrical reactor vessel of height 10 m and diameter 3.5 m, with approximately 440,000 pebbles of diameter 6 cm. Several designs in which the geometry is scaled down, but the pebble size is kept the same, have been considered, significantly reducing the number of pebbles required.

However, despite a large amount of study, there is still no complete theoretical description for how dense granular materials will flow, and hence no simple way to understand how pebble flow in a scaled facility will relate to that in the full-size geometry, or how this will affect pebble wear and dust generation. Granular flows have been of great interest in a number of different fields such as engineering (Levy and Kalman, 2001) and geology (Hutter et al., 1994; Hutter, 2005), and in the past two decades have attracted renewed interest from physicists (Jaeger et al., 1996; Kadanoff, 1999), particularly due to their relation to the glass transition (Liu and Nagel, 1998; Keys et al., 2007). Their rheology is complex, allowing for a solid-like behavior and the ability to support stress, but also exhibiting a transition to liquid-like flow (Aranson and Tsimring, 2001; Rycroft et al., 2009a). Granular materials exhibit many complexities at the level of a single particle, with forces being inhomogeneous (Mueth et al., 1998; Blair et al., 2001) and concentrated along extended force chains (Utter and Behringer, 2004; Majmudar and Behringer, 2005) making it difficult to define a continuum theory. In the slow, dense, quasi-static limit that is appropriate for modeling the pebble bed, the packing geometry of the pebbles themselves strongly influences the flow, since in order to move, pebbles must have enough space available to rearrange with their neighbors (Rycroft et al., 2006a).

In the absence of a theoretical description, the available data on granular flow in pebble-bed reactors consists of experimental studies in scaled-down geometries (Bedenig et al., 1968; Kadak and Bazant, 2004) or simulations carried out using the discrete-element method (DEM) whereby the position, velocity, and angular velocity of each pebble are individually tracked and updated according to Newton's Laws, using a frictional contact model to evaluate the forces that each pebble experiences. Due to the stiff contact equations required to simulate hard particles, DEM simulations are computationally intensive but are feasible on a parallel computer; they have been employed to analyze granular flows in many situations such as on inclined planes (Silbert et al., 2001) and static granular packings (Landry et al., 2003), and have been shown to be in good quantitative agreement with laboratory granular flows (Rycroft et al., 2009b). In relation to pebble-bed reactors, several DEM studies have examined the structure of static packed beds (Ougouag et al., 2005; du Toit, 2008), whereas others have analyzed flowing packings using both commercial software (Venter and Mitchell, 2007; Moormann, 2008) as well as in-house codes (Cogliati and Ougouag, 2006) that offer more flexibility to examine issues relevant to reactor design, including dust production (Cogliati and Ougouag, 2008). Full-size reactor simulations (Rycroft et al., 2006b) have been carried out and also compared to experiment (Jiang et al., 2012). The simulations can be used to analyze bulk flow features such as velocity profiles, but are also useful in determining pebble-based statistics such as pebble residence times and pebble diffusion, which may be useful in determining the propensity for rare events that could affect individual pebble peaking factors (Sobes et al., 2011).

In the current study, we aim to understand how flows in a scaled reactor will relate to the full-size geometry, and in particular investigate how pebble wear will differ. While the results are of direct relevance to the design of the proposed experimental facility, they also highlight the more general challenges in scaling of dense granular flows. We identify several areas where scaling presents some significant challenges, but also derive some general rules about how various quantities of interest will behave as a function of scale. Given the ambiguities in the frictional properties, we also systematically examine the role of friction. We place a particular emphasis on simulations with a Coulomb friction of $\mu = 0.35$. This value is consistent with the ranges reported by Luo et al. (2010) and we expect it to be a reasonable match to the conditions within the proposed facility. In a recent conference paper (Rycroft et al., 2012), we have also presented a variety of results for $\mu = 0.5$ for comparison.

2. Methods

2.1. Pebble contact model

The DEM simulations are carried out using the Large Atomic/Molecular Massively Parallel Simulator (LAMMPS) developed at Sandia National Laboratories (Plimpton, 1995; LAMMPS, 2005). The code is widely used and provides a framework for carrying out particle simulations interacting under a diverse variety of forces. For a given simulation domain, the code decomposes the domain into a rectangular grid of regions, assigning each to a separate CPU thread. Each thread is responsible for storing and updating the information about the particles in its region, and communicates with neighboring threads to handle cases where particles interact or move across region boundaries. To update the particle information, the code makes use of the explicit, second-order Velocity Verlet integration scheme with a fixed timestep—further details about the typical computational methods employed are discussed by Pöschel and Schwager (2005).

Here, we make use of modified version of the particle contact model introduced by Cundall and Strack (1979) that is suitable for simulating frictional hard spheres of diameter d. From this, a natural simulation time scale τ can be introduced according to $\tau = \sqrt{g/d}$ where g is the gravitational acceleration. Masses are scaled in terms of the pebble mass m. Throughout this paper, the results are specified in terms of these simulation scales, but they can be related to physical units at any time through specification of physical scales.