Segregation of Particulate Solids: Segregation via Convection

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(March 14, 1996)

I. INTRODUCTION

The segregation of granular materials is an effect of eminent importance for industrial operations and is subject to research since decades. Various experimental methods are used to measure the properties of granulates and to achieve information about the behavior of powders within the industrial environment, e.g. silos, hoppers, conveyor belts or chutes. However, important effects like size segregation are not yet completely understood and thus cannot be controlled under all circumstances. Experimental methods and theoretical approaches are nicely complemented by numerical simulations which in the last few years developed tremendously. For a review which covers a broad experience on segregation see Ref. [1] and Refs. therein. Different types of segregation are described and the factors affecting segregation are discussed extensively. Furthermore, theoretical approaches and methods for measurement and description of segregation are explained. In view of recent experimental and numerical results, we like to discuss here some more phenomena which were found to be important for size segregation.

A lot of effort has been invested in the understanding of basic effects in granular materials, such as heap-formation [2,3], convection [2,4,5] or size-segregation [6–12]. It turned out that segregation can be driven by geometric effects, shear, percolation and also by a convective motion of the small particles in the system [6]. Under many conditions, segregation due to convection appears to be orders of magnitude faster than segregation due to purely geometrical effects [7,8]. In rotating drums, an archetype of many industrial devices, several segregation processes acting in parallel are reported [13]; in three-dimensional devices, axial and longitudinal segregation are observed [14–16] simultaneously. For axial segregation, particle percolation is reported to be responsible [15], while longitudinal segregation is related to different surface flow properties in the cylinder [17,18]. However, there are still open questions which are subject to current research on model granular media [19,20]. New experimental techniques were recently developed to achieve detailed informations about the 'microscopic' quantities inside granular model systems. Model systems are assemblies of quite large spheres inside a two- or three dimensional system. We mention here recent experiments [7,8,21,19] for which different experimental setups and image processing techniques were developed, to follow the motion and also rotation of each particle. Furthermore, Ehrichs et al. [22] presented experiments where they examine granular convection with nuclear magnetic resonance imaging methods. Eventually, detailed experimental data will allow a comparison with various theories [23–29].

The main goal of this paper is to describe in Sec. II in how far convection may enhance segregation. Furthermore, we give a brief review of recent publications dealing with numerical simulations of discrete granulates in Sec. III, and we conclude in Sec. IV.

II. CONVECTION AS A MOTOR OF SEGREGATION

In Ref. [1] three basic types of segregation are discussed: Segregation in a powder bed, at the surface of a powder bed and in a fluidized powder bed. The first two types may be related mainly to geometrical effects such that the large particles rise to the top and the small particles move downwards to the bottom. The probability to fall down depends in general on the size of the empty space, beneath a particle, compared to its size. Thus downward motion is more likely for small particles. Note that the probability for downward motion is not only a function of size but also of shape, surface and density.

The simple argument above shows the importance of geometrical effects. However, this type of segregation due to geometry reasons only is rather slow for weak agitation [7,8], i.e. it leads to segregation speeds of several particle diameter per hundreds of vibration periods. This may be understood by the fact that the probability for large interstices is extremely small in a dense bed.

Besides shear, an effect we will not discuss in more detail here, an alternative motor of segregation is convection. In Ref. [6] experiments show that convection leads to fast size segregation. Assume powder in a vibrated container with rough boundaries. For accelerations larger than a critical threshold, the granulate is subjected to a ballistic flight and there is a relative motion between the container walls and the grains. Grains located at the vicinity of the boundaries feel a force which acts downwards in average [30,31]. A convective motion, downwards at the walls and upwards in the center of the container is the consequence. Convection and segregation were investigated experimentally [6,8,2,32] and also numerically [10,12,4,5,33–36] . Large particles are transported by those convective rolls in the upward direction where they remain trapped on the free surface since they are too large to be reinjected into the rather thin layer of downward flux near the boundaries. Convection may lead to rather large segregation speeds. If convection is limited to the upper layers of the bed geometrical effects may be dominant again in the lower part of the system [2,8,35].

Like in a fluidized bed, where the segregation also depends on the motion of the background fluid or gas, segregation in a mixture of two species may be driven by the flux within the system, i.e. convection, rather than by local reorganizations only.

III. NUMERICAL SIMULATIONS

In the last years, much effort was invested into the numerical modelling of granular media. Due to the increasing power of todays computer hardware it is possible to handle large particle numbers of rather arbitrary shape and size distribution in different geometries. Most of the simulations are performed using discrete element algorithms also termed molecular dynamics (MD) methods [4,5,33,37–39]. In addition, event driven (ED) algorithms [40–44,28,45,46] and Monte Carlo (MC)-like approaches [12,34] are used. MD and ED methods follow the particles trajectories in time based on different basic assumptions concerning the contacts of particles. In contrast, MC methods account for the random nature of granular materials by choosing one particle at random and applying different possible rules to move it. The connection between deterministic methods (MD and ED) and random methods (MC) is not obvious, since material dependent properties like dissipation and friction are not straightforward to include into the MC rules. Therefore we focus now on MD and ED methods, briefly describing the main features of both methods. Both simulation methods are based on assumptions about the particle-particle and particle-wall interactions. MD algorithms integrate Newton's equations of motion at e.g. fixed intervals of time, assuming contact forces in both, normal and tangential direction. For a recent review on possible interaction forces see Ref. [47]. For the sake of simplicity, one models granulates by spheres, with either, perfectly smooth or rough surface. Recent publications, using non-spherical particles [39], also take into account the asymmetric nature of, e.g., real sand. In contrast to the integration of forces in MD algorithms, ED algorithms evaluate the time of the next contact and compute the velocities of particles after the contact using a collision matrix scheme. In ED methods the time of contact of two particles is implicitly zero, fact which may lead to the 'inealstic collapse', i.e. a total loss of energy within a very short time [43,44,48,49]. For a comparison of MD and ED see Refs. [33,50,51], where a problem of MD, connected to the duration of contacts, i.e. the so called 'detachment effect', is discussed.

IV. SUMMARY AND CONCLUSION

In this paper, we pointed out the relevance of convection for segregation. If convection is strong and faster than geometric effects, segregation may be enhanced. Thus it is important to take care of convection in order to understand and control segregation. Furthermore, we presented a reference list of recent progress in the physics of granular media, including new experimental techniques and approaches, theories, and also a variety of numerical simulation methods.

Comparing the references of the present paper and of Ref. [1] we observe the existence of two distinct communities with only a small overlap of journals. On one side we find the engineering community with the experience and the knowledge of several decades and with the access to large scale industrial applications. On the other side we have the physicists community where new experimental methods were developped recently, including both, advanced technology and also model systems. Furthermore, new algorithms for computer simulations lead together with todays powerful hardware to a fast progress in the understanding of granular physics. The viewpoints, the questions, and the aims of both groups, engineers and physicists may be different but the goal, i.e. the understanding of granular physics, is common to both. Within this context, we hope that this paper is another step to bridge the gap and towards a better communication between both groups.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the European Community (Human Capital and Mobility) and of the PROCOPE scientific collaboration program. The group is part of the French Groupement de Recherche sur la Matière Hétérogène et Complexe of the CNRS and of a CEE network HCM.

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