Competition of Brazil nut effect, buoyancy, and inelasticity induced segregation in a granular mixture

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Abstract. It has been recently reported that a granular mixture in which grains differ in their restitution coefficients presents segregation: the more inelastic particles sink to the bottom. When other segregation mechanisms as buoyancy and the Brazil nut effect are present, the inelasticity induced segregation can compete with them. First, a detailed analysis, based on numerical simulations of two dimensional systems, of the competition between buoyancy and the inelasticity induced segregation is presented, finding that there is a transition line in the parameter space that determines which mechanism is dominant. In the case of neutrally buoyant particles having different sizes the inelasticity induced segregation can compete with the Brazil nut effect (BNE). Reverse Brazil nut effect (RBNE) could be obtained at large inelasticities of the intruder. At intermediate values, BNE and RBNE coexist and large inelastic particles are found both near the bottom and at the top of the system.

1 Introduction

It is known for decades that when a mixture of two types of granular particles are externally excited by means, e.g. a vibration, grains of different size, shape, mass or mechanical properties can mix or segregate. For instance in a mixture of small grains and one large intruder, when vertically vibrated, the intruder can go up [1] or down [2] – the so called direct and reverse Brazil nut effects, respectively. This effect hat has been studied in many papers (see, e.g. Ref. [3] and references therein), where different mechanisms have been proposed to explain the segregation phenomenon. For example, percolation, arching, void filling, convection, interstitial fluid effects, condensation, and some more have been invoked to be the cause of segregation. All these effects are explained in Ref. [3], although the problem is not completely understood yet. When both species have similar sizes (but possibly different) we can select few cases where a variety of segregation mechanisms and scenario appear [4–6]. For instance, in Ref. [7] particles of different masses, radii and restitution coefficients are placed in a dish which is horizontally vibrated, finding complete segregation. Segregation is also found in the same geometry when the grains have different friction coefficient with the base [8]. Under horizontal swirling, radial segregation of particles of different sizes has been observed [9]. In avalanches, grains of different shape segregate in stripes [10]; in partially filled rotating drums, axial size segregation develops [11]. In two dimensional systems under gravity, sinusoidally vibrated, clustering has been observed [12]. This segregation effect can be modulated by using non-sinusoidal vibration [13].

In some of the cases mentioned above the grain species differ on the friction or restitution coefficient. However few papers have studied segregation when this is the only difference between
grains. One of these cases is Ref. [14], where a mixture of spheres that only differ in friction coefficients (static, dynamic and rolling) is horizontally vibrated. They find complete mixing – that is, no segregation – for a flat plate while segregation is only observed when the plate was slightly inclined. Therefore, these results contradict the previously mentioned ones.

In a theoretical approach Ref. [15] constructs the hydrodynamic equations from the Boltzmann equation, finding inelasticity induced segregation. The authors explain the phenomenon as a consequence of the temperature gradient in the system induced by inelastic collisions, and relate the concentration gradient with the temperature gradient. In the same spirit, Ref. [16] studies the low density hydrodynamics of a mixture in the so called tracer limit, i.e., where the concentration of one of the components tends to zero. Among other results, they find that the temperature ratio of both species must be a constant. This constant value had been already measured by two experimental groups, both in 3D [17] and 2D [19] and by means of computer simulations in 3D [20] and 2D [21]. They found that the temperature ratio reaches a constant value in the regions of the system where the density is low. No tracer limit is needed. Generalization to moderate density has been done by Garzó [22] based on a kinetic approach using the Enskog equation for dissipative hard spheres.

Recently, it has been shown numerically that in moderately dense vibrofluidized granular matter, inelasticity induced segregation takes place [24]. When a mixture of grains of equal size and mass, but differing in their restitution coefficient in put in a vibrating box, the more inelastic grains sink, segregating partially with the other species. In this paper we study if this inelasticity induced segregation can compete with two other known mechanisms of grain segregation: buoyant forces when grain densities differ and the Brazil nut effect when their sizes differ.

The structure of this paper is as follows. In Section 2 we describe the system under consideration. Section 3 reproduces the results presented in Ref. [24] regarding the macroscopic segregation of two species differing only in their restitution coefficient. Section 4 analyzes the competition with buoyant forces, when considering grains of equal size, but different masses and restitution coefficients. Section 5 studies the competition with the Brazil nut effect when grains of the two species have the same density, but differ in size and restitution coefficients. We conclude with Section 6 summarizing the results of the paper.

2 Description of the system

We study the effect of the difference on restitution coefficients in the segregation phenomenon, by means of Molecular Dynamics simulations of a bidimensional granular mixture of two types of particles, $A$ and $B$. Grains are modeled as smooth Inelastic Hard Disks, but differing on the normal restitution coefficient that characterizes their inelastic collisions. The two species can also differ in their masses $m_A$ and $m_B$, and in their diameters $\sigma_A$ and $\sigma_B$. The restitution coefficient for $A-A$ collisions is $\alpha_A$, for $B-B$ collisions is $\alpha_B$. For the interparticle collisions $A-B$ we have taken $\alpha_{AB} = (\alpha_A + \alpha_B)/2$. Usually we will consider that $B$ are the most inelastic particles ($\alpha_B < \alpha_A$).

We have taken a fixed total number of particles $N_T = N_A + N_B$, changing the concentration of the $B$ particles. For the simulations reported in this paper, we have fixed $N_T = 680$ disks and varied $N_B$ from 10 (that can be considered as a tracer limit) until 160. The disks are placed under the action of a gravitational acceleration $g$ pointing downward in a rectangular box of width $L_x = 50\sigma_A$, infinite height, and with the bottom wall oscillating periodically at high frequency $\omega$ and small amplitude $A$, with a bi-parabolic waveform [25]. Periodic boundary conditions are used in the horizontal direction. They avoid the appearance of convective rolls by the influence of the walls. Under these conditions, the system reaches a stationary state with gradients in the vertical direction [26].

Units are chosen such that $\sigma_A \equiv \sigma = 1$, $m_A = 1$ and $k_B = 1$. The time scale is fixed by the characteristic energy of wall oscillation, that is $m_A (A \omega)^2 = 1$. Simulations are performed with a fixed value of the gravity acceleration $g$ in order to reduce the parameter space and provide a more detailed analysis on the effect of inelasticity. The value of $g = 0.15$ (in our units), was