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Spatially periodic modulated thermal convection in granular fluids: A simulation study

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ABSTRACT

Rayleigh-Bénard convection in normal fluids shows interesting variation when a boundary is temperature modulated. As granular fluids show quite good resemblance to normal fluids, it is expected that they exhibit similar variation in convective dynamics under such a condition. A study of convection in granular fluids by injecting spatially non-uniform energy through a boundary is done in this paper. Emphasis is made on the dependence of onset and strength of granular convection on the relevant dimensionless parameters characterizing the convective state. The non-uniform energy injection is modelled by spatially periodic modulation of the lower boundary. It is seen that the amplitude and the wavelength of the periodic modulation are two new important parameters characterizing the dynamics.

1. Introduction

Buoyancy driven convection in normal classical fluids is an old and well studied problem [1,2]. It is known that granular fluids can exhibit convective instability under certain excited states [3–11]. In the former case the negative thermal gradient necessary for convection is externally imposed [2], whereas in the latter case it is spontaneously developed due to a combined effect of dissipation due inelastic collisions and gravity [7].

Convection in granular fluids can be categorized into two types, namely, boundary driven and buoyancy driven convection. In past relatively more attention was given to the former one and several numerical and experimental studies were done to understand various aspects of it [8,9,12,14-18], whereas the latter one received attention in the beginning of this century after Ramírez et al. [7] observed it, for the first time, in numerical simulations. Later, hydrodynamic formulation of thermal convection was given for some simplified granular fluid models [5,13,19]. Experimentally, it was first seen by Parker et al. [11] and, thereafter, some studies [4-6,20] were done to understand the phenomenon.

Convection of normal fluids over patterned surfaces is of immense practical importance [21–24]. A surface is called a patterned one if, for instance, local geometry, material property, and/or temperature varies with position. In this paper the problem of convective dynamics of a granular fluid in the presence of a surface patterned by means of temperature modulation using an event driven molecular dynamics (EDMD) simulation [25] is addressed. A monodisperse granular matter is filled in a wide container which has spatially periodic modulated bottom surface. A simple model is chosen in order to facilitate futuristic theoretical advancement of the convective dynamics of granular fluids under such a condition using a hydrodynamic theory. The convective state in a monodisperse dilute granular fluid is known to be determined by a set of four dimensionless control parameters [13,19]. It is seen in this paper that the nature of spatially periodic modulation of boundary adds two more to their list. All of them are discussed in Section 2. My aim is to numerically find the dependence of the control parameters, determining the convective dynamics of the system driven in a temperature modulated container, on the strength of convection.

The paper is organized as follows. In Section 2 model and simulation, description of the model, the simulation technique, the boundary conditions, the parameters, and the quantities used in this study are defined. In Section 3 the effect of the relevant parameters on the onset of convection is discussed. In Section 4 the findings are summarized and conclusions are presented.

2. Model and simulation

A 2d system of N monodisperse hard disks confined in a wide rectangular container is studied using EDMD simulation method. The system is driven by a succession of thermal baths along the length of the container, normal to the gravity, at the bottom. The bottom of the container acts as a spatially periodic modulated thermal boundary

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as shown in Fig. 1. The periodicity of temperature modulation is achieved by a square wave temperature profile $\Theta(x)$ which is horizontally symmetric about the centre of the container such that the mean temperature of the bottom wall T_b, spatially averaged over length L_x, remains unchanged. Note that the modulated temperature profile does not change over time, therefore, steady state properties of the system can be found. Each thermal bath is modelled by a probability velocity distribution [26,27]. Its general form is given as follows:

$$P(v^n) = \frac{v^n}{\Theta(x)} \exp\left[\frac{-(v^n)^2}{2\Theta(x)}\right], \tag{1}$$

where v^n is the normal component of the velocity of a disk just after colliding with the bottom at position x where a thermal bath has the temperature $\Theta(x)$, which determines the width of the distribution. Thus, whenever a particle collides with the base it is reinjected with the normal component of velocity chosen from $P(v^n)$, while the tangential component of the velocity is kept unchanged so that there is no shear effect due to walls. The side and top walls are rigid, smooth, and elastic which play no role in triggering convection. Particle-particle collisions are governed by a constant restitution coefficient e. The collisions conserve momentum, but dissipate kinetic energy such that,

$$\left(u_{ij}^n\right)' = -e u_{ij}^n, \tag{2}$$

where u_{ij}^n and $\left(u_{ij}^n\right)'$ denote the normal components of the relative velocities of a pair of particles before and after collision, respectively. Length, mass, and time are measured in units of grain radius r, grain mass m, and $\sqrt{r/g}$, respectively. The simulation parameters, namely, m, r, tangential restitution coefficient e_t, restitution coefficient of the side and top walls e_w, and acceleration due to gravity g are all set to unity and kept unchanged. The other simulation parameters, namely, system size $N = 20{,}700$, length $L_x = 900$, and height $L_z = 300$ are kept unchanged.

2.1. Hydrodynamic fields and control parameters

To study the relevant hydrodynamic fields such as velocity, density, and temperature the area of the system is coarse-grained by dividing it into identical square cells of sufficiently large size. The field variables are defined for simulation as given in Ref. [9], but

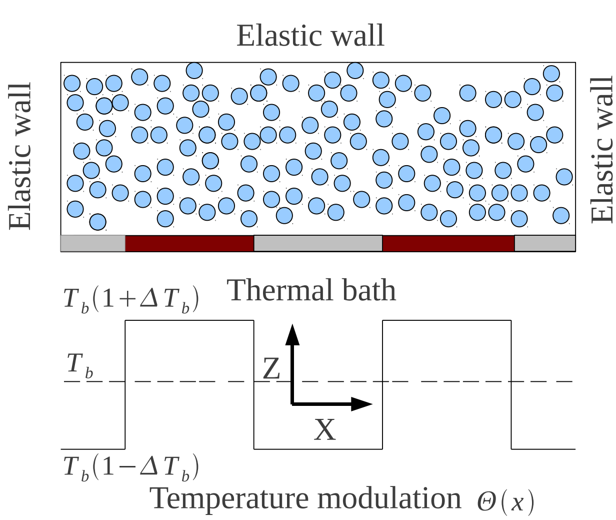

Fig. 1. Schematic diagram showing thermally excited monodisperse system with elastic top and lateral walls. A sample temperature modulation is also shown.

with mass fraction replaced by particle mass, which is one, as the coarse-graining cells are much larger than the grain size. Let $n(x,z,t)$ denotes the number of particles in the cell at (x,z) at time t. Then, the instantaneous local velocity in the cell at (x,z) is given as,

$$\mathbf{u}(x,z,t) = \frac{\sum_{k\in(x,z)} \mathbf{v}_k(t)}{n(x,z,t)}, \tag{3}$$

where $\mathbf{v}_k(t)$ denotes instantaneous velocity of the k^{th} particle.

Now, the time averaged local hydrodynamic velocity field is given as,

$$\mathbf{u}(x,z) = \langle \mathbf{u}(x,z,t)\rangle_t \tag{4}$$

$$= \frac{1}{t_{ss}} \sum_t \mathbf{u}(x,z,t), \tag{5}$$

where t_{ss} gives the time interval over which the steady state average is obtained.

The magnitude of the instantaneous fluctuating velocity at (x,z) is given by,

$$|\mathbf{C}(x,z,t)| = \left(\frac{\sum_{k\in(x,z)} (\mathbf{v}_k(t) - \mathbf{u}(x,z,t))^2}{n(x,z,t)}\right)^{1/2}, \tag{6}$$

then, the local temperature field is given by,

$$T(x,z) = \frac{1}{2}\left\langle |\mathbf{C}(x,z,t)|^2 \right\rangle_t \tag{7}$$

$$= \frac{1}{2t_{ss}} \sum_t |\mathbf{C}(x,z,t)|^2 \tag{8}$$

The mass density of particles at the location (x,z) is calculated from

$$\rho(x,z) = \frac{1}{\delta A}\langle n(x,z,t)\rangle_t \tag{9}$$

$$= \frac{1}{t_{ss}\delta A} \sum_t n(x,z,t), \tag{10}$$

where δA is the area of a coarse-graining cell.

Similarly, it is straightforward to define the field variables associated with horizontal rectangular stripes. They take the following forms. The time averaged local hydrodynamic velocity field at z is given as,

$$\mathbf{u}(z) = \langle \mathbf{u}(z,t)\rangle_t \tag{11}$$

$$= \frac{1}{t_{ss}} \sum_t \left(\frac{\sum\limits_{k\in(z)} \mathbf{v}_k(t)}{n(z,t)}\right), \tag{12}$$

The local temperature field at z becomes,

$$T(z) = \frac{1}{2}\left\langle |\mathbf{C}(z,t)|^2 \right\rangle_t \tag{13}$$

$$= \frac{1}{2t_{ss}} \sum_t \left(\frac{\sum_{k\in(z)} (\mathbf{v}_k - \mathbf{u}(z,t))^2}{n(z,t)}\right), \tag{14}$$