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GRANULAR FLOW IN THE PRESENCE OF AN ELECTRIC FIELD

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The granular flow in a vertical pipe in the presence of electric field E is studied. Depending upon its initial state and the applied field voltage the controlled flow rate remains in two phases, dilute flow or dense flow. For dilute flow, the electric field has no effect on the flow rate until V reaches a critical value V_1. At $V = V_1$, the flow rate drops abruptly and a transition of the particulate from dilute to dense flow occurs. For dense flow, the flow rate decreases monotonically with increasing V. A two-dimensional computer simulation has been done and the results agree qualitatively well with the experimental measurements.

1 Introduction

Granular matter, which can exhibit solidlike and liquidlike behavior, has attracted much attention in recent years not only because of its ubiquity in nature and application in technology, but also because of the poor understanding in its basic mechanism [1-4]. The study of granular flow in a vertical pipe is one of the most challenging projects in the field, and many interesting phenomena have been observed [5-9]. Considering the ER effect induced by an applied electric field, we are interested in finding out what happens if an electric field is applied to a granular flow.

Electric field was found to be useful to regulate and control the granular flows in many industrial processes, such as in the electrospouted bed [10], the electrofluidized bed [11] and the electrostatic valve [12]. Electric field may also be a powerful tool to gain understanding of the dynamics of granular flows [13, 14]. In this work we report our study on the behavior of granular flows in a vertical pipe by applying a horizontal ac electric field. Some interesting phenomena have been observed:

(1) the granular flow is retarded beyond a critical electric field V_1 when V increases. For $V < V_1$, the flow rate is unaffected by V and keeps a constant value Q_0. The flow rate abruptly drops at V_1 and then decreases with increasing V for $V > V_1$;
(2) in a reverse process, if we first apply an electric field of voltage $V > V_1$ to the flow, the granules become densely filled above the electrodes. We then decrease the voltage to a desired value V to measure the flow rate at that voltage, we find that the flow rate increases continuously as V decreases, and reaches Q_0 at V_2, which is lower than V_1; and
(3) if the electric field is high enough a granular arch is formed at the region of the electrodes. A computer simulation is performed and the results agree qualitatively with the measurements.

2 Experimental setup

The experimental setup is schemed in Fig. 1. Nickel spheres of an average diameter d = 0.25 mm is filled in a glass hopper placed on top of a glass pipe with inner diameter of 3mm and 100mm in length. The metallic particle is chosen for less electrostatic effect. Two parallel flat copper electrodes 4.4mm apart, 15 mm in height and 12 mm in width, are attached to the outside walls of glass pipe. A 50 Hz ac electric voltage V is applied

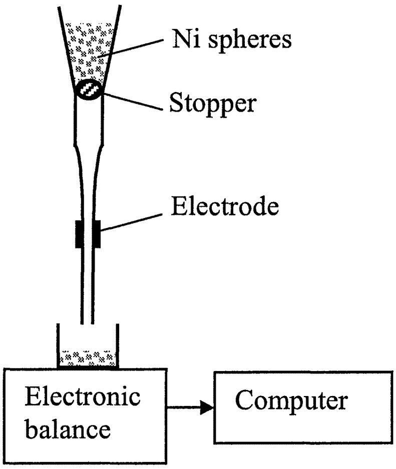

Figure 1. Scheme of experimental set up.

across the electrodes. The granular flow is initiated by pulling the stopper, which is inserted at the outlet of hopper. A weighing sensor with sensitivity of 0.02 g and recording rate of 0.02 s is applied at the bottom of the pipe. By measuring the granular mass at each desired electric voltage, the dependence of flow rate vs. voltage can be obtained.

3 Experimental results and computer simulation

When we apply an electric field E of 0 V/mm and 1200V/mm alternatively with an interval of several seconds, the mass M(t) measured as a function of time t shows a slope difference: the slope is higher at E = 0 and lower at E = 1200 V/mm as shown in Fig. 2. This phenomenon indicates that the granular flow can be retarded by electric field.

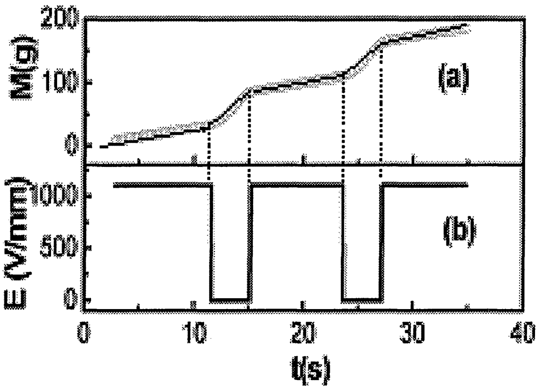

Figure 2. Relation of flow mass (a) vs. applied pulse electric filed (b).

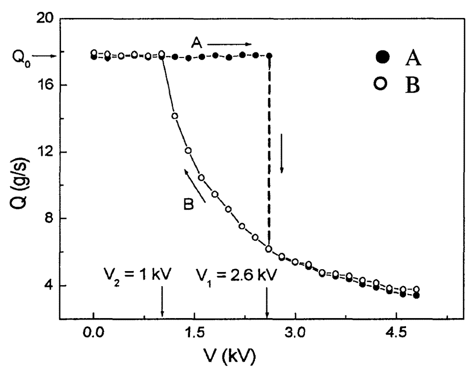

Figure 3. Flow rate Q vs. the applied voltage V. **A** and **B** indicate different processes. The arrows represent the direction of applied voltage.

If we change the applied voltage in steps, how does the voltage influence the granular flow? The following two processes are applied:

In the first process (denoted as A), we measure the flow rate at each desired voltage in a range from 0 V to 4.8 kV with an interval ΔV= 0.2 kV. In the second process (denoted as B), V is first fixed at a voltage 4.8 kV and then lowered to a desired voltage from 4.8 kV to 0 V with an interval of 0.2 kV. The flow rate Q vs. V is plotted in Fig.3. It can be seen that in process A, the granular flow keeps a constant value Q_0 with increasing V until $V=V_1$= 2.6 kV. Flow rate Q drops abruptly when we increase the voltage by a small amount (as small as 0.02 kV) higher than V_1. When we further increase the voltage, Q decreases gradually with increasing V. In process B when lowering the voltage, however, Q increases continuously without any sudden jump and reaches Q_0 at a voltage V_2 (1.0 kV). In the two processes flow rates follow the same Q(V) curve in the region between V_1 and 4.8 kV. The curve can be fitted approximately as $Q = CV^{-1}$, where C is a fitting parameter.

In the experiments we have observed that particles converge to the sidewall of the tube near the top edges of the electrodes as V increases. Particles near the sidewall thus move slower than that in the central part. Eventually when the voltage is high enough, at and above V_1, an unstable arch across the tube at a position near the top edge of the electrodes is formed as shown in Fig. 4. It can be seen that some particles in the arch fall

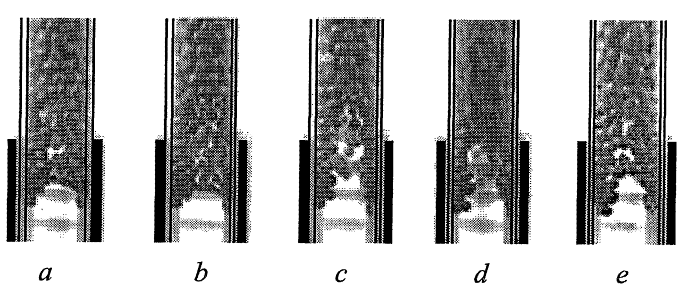

Figure 4. The unstable arch formed at high voltage. Pictures *a* to *e* were taken at a time sequence in an interval of 1/25 second.

randomly resulting a lower flow rate at high voltage.

To understand the mechanism behind, an analysis is proposed and a computer simulation is done.

We first consider the case of process A. The force acting on the polarized particle in an inhomogeneous electric field can be expressed as

$$\vec{f} = -\nabla(-\vec{p}\cdot\vec{E}) = 4\pi\varepsilon_0 R^3 \nabla E^2 .$$

When the electric field is high enough to affect the motion of the particles, i.e. the interaction is comparable to the kinetic energy of the falling particles, the particles will be dragged by the gradient of field and converge to the sidewall near the top of the electrodes as shown in Fig. 5. The arrows in Fig.5 represent the direction of the dragging force. This force against the sidewall induces a friction between particle and wall, which will reduce the velocity of particles along the wall. The attraction of polarized particles cause the particles moving closer and enlarges the local field between particles. The enhancement of local field between particles will further increase their mutual induction and cause particles to interact with each other and aggregate stronger. This positive-feedback effect, we believe, is the major contribution which causes the flow rate dropping dramatically at V_1. In fact there is a transition from dilute flow to dense flow occurred at V_1. When $V< V_1$ the remaining opening at the central area of converged particles in pipe is large enough for the particles passing through as a dilute state flow. The flow remains at a constant rate $Q = Q_0 = \rho v S$, where ρ and v are the average density and average velocity of particles, respectively, and S is the effective cross-sectional area. Although the v and S are reduced due to the electric field induced converging effect, the increase in ρ ia able to assure Q (= ρvS) to remain a constant Q_0 until V reaches a critical voltage V_1. At this voltage the density ρ reaches its maximum value, and it becomes dense flow for $V > V_1$.

In process B, the flow rate vs. voltage shows power law decay vs. V as described above, $Q=CV^{-\beta}$ and $\beta\approx1$ in our experimental condition. Although the mechanism is still not yet clear[15], the rate of dense particle flow from a hopper can be expressed as $Q\approx aD^{5/2}$, where D is the diameter of outlet. Therefore, the electric field plays a role here as an effective opening in the case of dense flow, i.e. increasing voltage corresponds to decreasing the size of the opening.

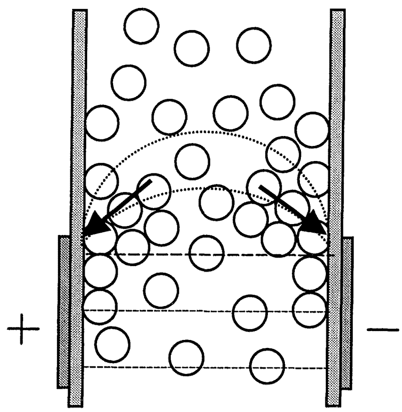

Figure 5. Sketch of the force acting on particles due to the field gradient in the region of electrodes. Dashed lines indicate electric lines in between electrodes.

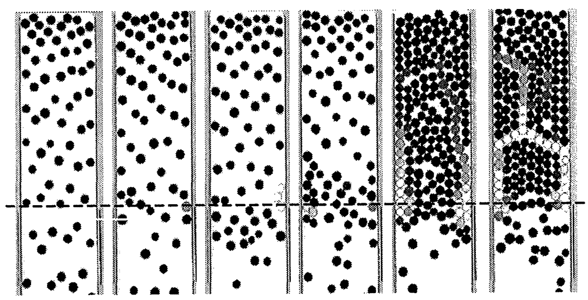

Figure 6. Two-dimensional simulation: particles in the pipe at different voltages. Dashed line indicates the top edge of electrodes.

Therefore, by applying the electric field higher than a critical voltage the initial dilute flow can be transferred to a dense flow, corresponding to a sudden drop of flow rate. This phenomenon may be similar to that of a first order phase transition. A quantitative explanation is still absent.

A two-dimensional model was proposed to simulate the granular flow under the electric field. The computer simulation is based on molecular dynamics model in which the interaction and friction between polarized particles and wall, the collision as well as the motion of particles under gravity were taken into account. The simulation results on the distribution of particles in the pipe and the flow rate Q vs. voltage V are plotted in Fig. 6 and Fig. 7 respectively. It can be seen that particles converge to sidewalls and slow the speed of particles above as voltage increases. There is a critical value $V=V_1\approx 5.6$ kV at which the particles become dense in the region above the electrodes. These pictures show that the granular flow is thin when $V< V_1$ while the flow is dense when $V\geq V_1$. The behavior of Q vs. V shown in Fig. 7 is consistent qualitatively with the experimental measurements as showed in Fig. 3.

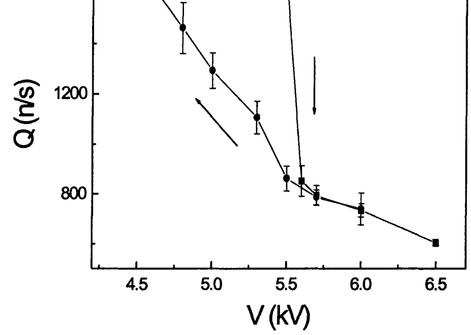

Figure 7. Two-dimensional simulation: dependence of flow rate vs. voltage. The arrows indicate the direction of the applied voltage.

4 Conclusions

By applying an electric field to the granular flow in a vertical pipe we have observed some novel phenomena. Applying an electric field to a dilute flow, we find that the flow rate is unaffected by V and remains as Q_0 till V reaches a critical value V_1. At $V = V_1$ the flow rate drops abruptly, and decreases with increasing V. In a reverse process, when V decreases from a value $V > V_1$, the flow rate increases continuously with decreasing V and reaches Q_0 at V_2. At V_1 the transition from thin flow to dense flow occurs, which is similar to a first order phase transition. The unstable arch is formed near the top edge of the electrodes as the electric field is high enough. A computer simulation is performed, and the result of which agrees qualitatively well with the measured behavior.

Acknowledgements

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