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Intermittent granular flow in the presence of an electric field

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Abstract. – In this letter experimental observations of vertical-pipe granular flow in the presence of an electric field are reported. Granular nickel particles flowing down a vertical pipe are found to be retarded by a local horizontal ac electric field when the field voltage V is greater than a critical voltage V_{c}. For $V < V_{\mathrm{c}}$, the steady-state flow rate is practically unaffected by V. The flow rate decreases discontinuously at V_{c}, and then decreases gradually for $V > V_{\mathrm{c}}$. Physically, particle clusters are formed above an arch interface, which exists in the electric-field region when $V > V_{\mathrm{c}}$. The vertical flow consists of clusters intermittently dropping off from the interface. A transient density wave with wavelength lengthened by electric field is also observed.

Granular matter, which can exhibit solidlike and liquidlike behavior [1,2], is a very interesting dynamical system. Granular flow is a nonequilibrium system waiting for a good theoretical description. The importance of this system stems from its ubiquity in nature and applications in technology (such as mining, agriculture and construction), and as an example in complex systems [3]. Even its basic behaviors are intriguing. For example, size segregation [4], force fluctuations [5], global and localized excitations [6], spontaneous stratification [7], density waves [8, 9] are observed but not fully understood. A localized disturbance, to induce new excitations or to alter the behavior of the granular matter, would be of help in elucidating the mechanism of these phenomena. Electric field, being used in flow control of particulate material for bulk transport of agricultural seeds [10] and in electrospouted beds [11], provides us with a good control method in understanding the dynamics of the granular flow.

In this letter, i) a localized electric field is shown to be able to control the granular flow of nickel particles in a vertical pipe. The flow is retarded when the field is large enough. ii) Clusters induced by oil [12], by shaking [13], or by electrostatic force [14] play important roles in the behavior of granular matter. Here, a new method of inducing the formation of clusters by the use of an electric field is introduced. iii) Granular flow and traffic flow share a lot of similarities [13,15]. The formation of local clusters due to an electric field corresponds to

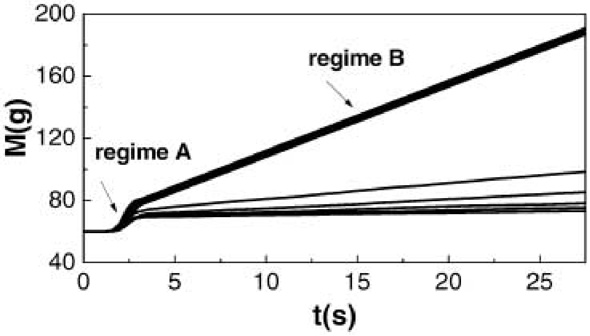

Fig. 1 – Dependence of mass M on time t. The electrode voltage V is fixed for each curve, which increases from 0 to 3 kV, at an interval of 0.25 kV, starting from the upper to the lower curve. In regime B, the upper (low-V) group of curves has practically the same slope, while the lower (high-V) group, with $V \geq 2\,\mathrm{kV}$, has slopes decreasing with V.

the artificial creation of traffic jams in the traffic problem. A granular flow in the presence of an electric field may provide a new modeling system for studying traffic [16,17]. iv) Recently density waves have been observed in the granular flow in a vertical pipe, which was inserted into a flask of air [9]. The exact mechanism of these waves is not yet clear, even though the drag between air and particles is definitely involved [18]. Here, a transient granular density wave whose wavelength can be lengthened by an electric field is reported.

A vertical glass pipe of 94 cm length and inner diameter D ($= 2\,\mathrm{mm}$) was attached to the bottom of a hopper. Two vertical copper-plate electrodes of 10 cm in height and horizontal separation of w ($= 4\,\mathrm{mm}$) were fixed to the outside of the glass pipe. The top of each electrode was 28 cm below the base of the hopper. Granular particles were metallic nickel spheres, of diameter d ($= 0.35\,\mathrm{mm}$) on the average. An electronic balance with 1 mg sensitivity and a weighting period of 0.4 s was used to measure the mass flow rate of granular particles coming out of the pipe. A plate placed at the bottom of the pipe acts as a stop; nickel spheres were poured into the pipe and filled up the hopper to a fixed height. The granular flow was initiated by pulling the plate horizontally away from the pipe.

The mass M measured by the balance as a function of time t is shown in fig. 1. For each $M(t)$ curve, an ac voltage V of 50 Hz applied across the electrodes is fixed, varying from 0 to 3 kV, at an interval of 0.25 kV (and then from 1.6 kV to 2.3 kV, at an interval of 0.1 kV, which is not shown in fig. 1). There are two regimes in each $M(t)$ curve. In regime A, the particles in the pipe rushed down quickly, and the flow turned to regime B. In regime B, for the low-V group, corresponding to $V < V_\mathrm{c}$, the particles came mainly from the hopper. For the high-V group, corresponding to $V > V_\mathrm{c}$, particles were retarded in motion when passing through the electric-field region and the particles piled up densely above the electrode region. The steady-state flow rate Q obtained from the slope, in regime B, of each $M(t)$ curve is plotted *vs.* V in fig. 2. It is found that there exists a critical voltage V_c ($= 1.9\,\mathrm{kV}$), at which Q drops abruptly. When $V < V_\mathrm{c}$, Q remains a constant Q_0, and for $V > V_\mathrm{c}$, Q decreases gradually as V increases. The $Q(V)$ curve, for $V > V_\mathrm{c}$, is enlarged in the inset of fig. 2, and was able to be fitted with a power law decay, $Q = a + b(V - V^*)^{-\alpha}$. The mechanism of this behavior is not yet quantitatively understood. However, we note that the discontinuous change of $Q(V)$ at V_c in this nonequilibrium system is analogous to that of a first-order phase transition in equilibrium systems [19].

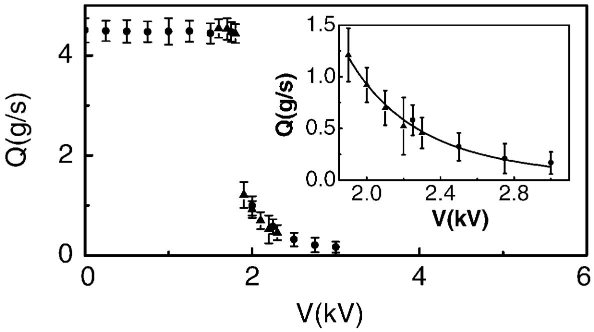

Fig. 2 – Dependence of flow rate Q on V, where Q is obtained from the slope of the $M(t)$ curve in regime B. The solid dots and triangles represent the two series of experimental runs. The $Q(V)$ data points above the transition voltage, *i.e.* at $V > 1.9\,\mathrm{kV}$, are plotted in the inset, and are fitted to a power law decay curve. For the run shown, the fitted line in the range of $1.9\,\mathrm{kV} < V < 3\,\mathrm{kV}$, $Q = 0.04 + 1.25(V - 0.88)^{-3.08}$.

When $V > V_c$, an arch interface (see fig. 3) was formed inside the electric-field region, slightly below the top of the electrodes. Below this arch the mass density was very small. (Note that the arch was absent for $V < V_c$.) The arch interface was like a bridge being broken and rebuilt continuously in time. In fig. 3(a), the bridge forms; in fig. 3(b), the bridge is sustained and the granules above the bridge readjust slightly. In fig. 3(c), the bridge is broken; and a cluster of granules is dropping down in fig. 3(d). (The blurred image shows that the breakaway cluster is moving fast.) The bridge is rebuilt in fig. 3(e), and the velocity of

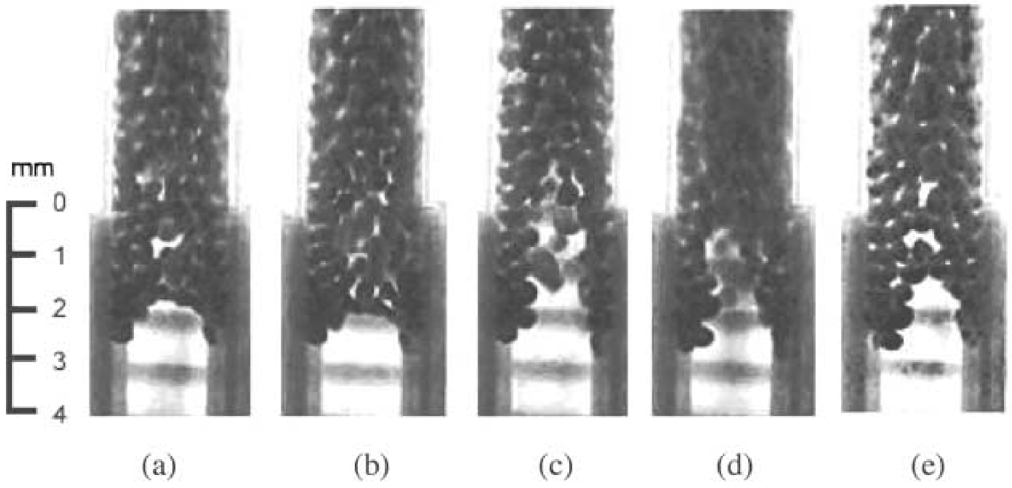

Fig. 3 – Time sequence of video images of the arch interface observed (in regime B) near the top of the electrodes. $V = 3\,\mathrm{kV}$. Time increases from (a) to (e) at an interval of 0.08 s between adjacent images. The horizontal scale bars are 1 mm apart from each other. The irregularly shaped, white spots in the lower half of the images (where the electrodes are located) are due to gaps between the granules. The small, round white spots in the upper half are not gaps, but are due to reflection of light from the surfaces of the granules.

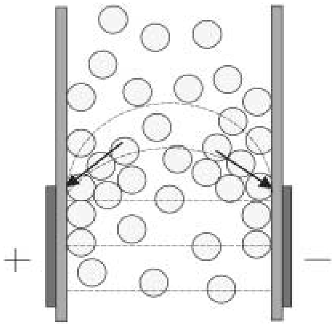

Fig. 4

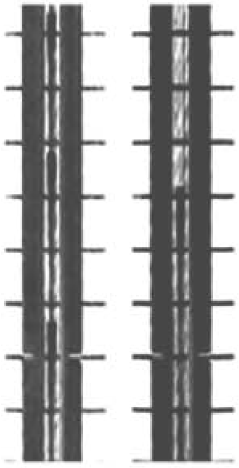
(a) (b)

Fig. 5

Fig. 4 – Illustration of the force acting on particles due to the field gradient in the electric-field region. Dashed lines indicate electric lines in between the two electrode plates.

Fig. 5 – Images of density wave observed in the electrodes region. The pipe was 85 cm in length; its inner diameter is 3 mm and its outer diameter is 5 mm. The top of each electrode was 20 cm below the base of the hopper. The electrodes are 40 cm in height and show up as the two outer black columns in each image. The horizontal scale bars are 2 cm in separation. (a) shows the existence of a density wave when $E = 0$. (b) shows the wave with elongated wavelength when $E = 4 \times 10^5$ V/m.

granules above the bridge slows down again. The flow in the pipe is therefore an intermittent flow. As V was increased, the bridge was able to sustain itself for a longer period of time.

To understand the mechanism of the electric field interacting with a granular flow, a schematic drawing of the force acting on the particles in the field is presented in fig. 4. Particles are polarized in the electric field, and the force acting on the polarized particles in an inhomogeneous electric field depends on the field gradient. When this interaction is comparable to the kinetic energy of the falling particles, particles will be dragged by the gradient of the field to converge to the sidewall near the top of the electrodes, as shown in fig. 4. The arrows in fig. 4 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 causes the particles to move closer and enhances the local field between particles. The enhancement of the local field between particles will further increase their mutual induction and cause particles to interact with each other and aggregate. This positive-feedback effect, we believe, is the major contribution which reduces the flow rate dramatically at V_c. In particular, the interaction between polarized particles provides an adhesive force and thus enhances the tendency to form clusters.

An intermittent arch begins to form when the frictional force enhanced by the electric field E (proportional to E^2 in the case of dipole-dipole interaction) is comparable with the weight of the particle. An order-of-magnitude estimate based on the dipole-dipole interaction gives a threshold $E_c = 7 \times 10^5$ V/m, which is of the same order of magnitude as the experimental value of 4.75×10^5 V/m, where $E = V/w$ (w is the electrode separation).

The electric field E was found to be able to affect the formation and characteristics of the density waves in the pipe. The influence of the electric field was observable when the electrode length was sufficiently long. For this we changed the electrode length to 40 cm and the pipe inner diameter to 3 mm.

When $E = 0$, a density wave formed quickly in the pipe right after the flow was initiated. As shown in fig. 5a, the dark triangle parts inside the pipe represent the packed granular clog, and the light parts represent the bubbles in which the density of granules is dilute. All structure moved upward very quickly and disappeared in 2-3 seconds. The formation of this density wave is due to the air effect, as similar to the density wave reported by Raafat *et al.* [8]. In our experiment, particles were filled in a long pipe at first. A density wave pattern was formed at the first 2 to 3 seconds when air from outside the pipe pushes in to fill the low air-pressure gap induced by the sudden down-flow of the particles during the initiation of the flow.

When electric field was applied, the adhesive force provided by the interaction between the polarized particles caused the merging of clogs, which intended to form longer clogs with a much slower upward veolocity. The lifetime of the density wave was prolonged to 5-8 seconds. As E went higher ($= 4 \times 10^5$ V/m), as shown in fig. 5b, a long clog even remained stationary for 2-3 seconds and then flowed out of the pipe. The density wave disappeared when E went further higher as the intermittent arch formed.

In conclusion, we present our experimental observations that an electric field can influence and control the granular flow of nickel particles. The field can enhance the formation of clusters through induced dipoles in the particles. Arched interfaces are formed in high fields, giving rise to new, intermittent flow patterns. Furthermore, air-flow–induced mass density waves are observed being modified by the electric field. The fact that an arch can be induced by an electric field provides a new control parameter in the general study of arches in granular matter, and should help in understanding the formation mechanism.

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