Retardation and transitions of dilute and dense granular flows in a vertical pipe induced by electric fields

Wei Chen,[a] Meiying Hou, Kunquan Lu, Zehui Jiang,[b] and Lui Lam[c]
Center for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

(Received 28 September 2001; accepted for publication 15 January 2002)

Granular flow of nickel particles down a vertical pipe from a hopper is shown to be retarded by a horizontal ac electric field applied to a local region along the pipe. The particles are released from the hopper by pulling out a stopper in the hopper. Two sequences of experiments with different initial flow conditions are performed. In the first sequence, a *dilute* flow in the pipe is created after a fixed voltage V ($\leqslant$4.8 kV) is applied across two short, vertical copper electrodes. The steady-state flow rate Q remains practically constant for $V<V_1$ (=2.6 kV). At $V=V_1$, Q drops abruptly; the drop depends on the location of the electrodes. For $V>V_1$, the flow becomes *dense*; Q decreases with a power law, $Q\sim V^{-1}$. In the second sequence of experiments, V is first set at 4.8 kV; the flow is allowed to start, and soon becomes a *dense* flow; then, V is reduced to the desired voltage. The new, steady-state Q vs V curve coincides with the previous $Q(V)$ curve of the first sequence, except for $V_2<V<V_1$, where $V_2=1.0$ kV. The voltage V_2 is a continuous transition point at which Q changes from a dense flow ($V>V_2$) to a dilute flow ($V<V_2$). Our results show that a large enough ac electric field can decrease the flow rate of a dilute or dense flow; the critical voltage that can reduce a dense flow, V_2, is less than that for the dilute flow, V_1. [DOI: 10.1063/1.1459767]

Granular matter is a unique system that exhibits solidlike and fluidlike properties.[1,2] Their peculiar properties can be attributed to the strong contact interactions and inelastic collisions between particles. Introducing a long-range interaction to compete with this short-range contact force can provide a new control parameter in elucidating the underlined mechanism.[3] Electric field is such a long-range force offering an opportunity compared to mechanical techniques to explore granular dynamics.

Controlled by electric field, particle clustering and phase transition from a granular solid phase to a gas phase were formed and studied by Aranson[4] and co-workers. Electric field was also investigated and used for industrial processes to control and regulate the bulk transportation of semiconducting particles such as agricultural seeds.[5] Other applications include being used in the spouted bed[6] to regulate the solid recirculation rate, and in packed and fluidized beds[7] to effectively alter the bed dynamics.

The granular flow down a vertical pipe in the presence of an electric field was studied in our previous work. Phenomena including arch formation and wavelength elongation of a density wave under electric field were observed.[8] It was also found that the local electric field was able to retard the downward movement of a dense column of particles, but was ineffective in doing so when the column of the particles was dilute in density.[9]

In order to understand the electric-field effects on the dense and dilute flows, respectively, in this work we prepare the system in two particular sequences to separate the dilute and dense flows for study. We find that the field effects are very different indeed depending upon the initial flow conditions. For dilute flow, the electric field has no effect to the flow rate when the voltage applied to the electrodes is low. As the applied voltage V is higher than a critical voltage V_1, the dilute flow transforms to dense flow and the flow is retarded. For dense flow, the field retards the flow rate monotonically when the voltage is higher than a different voltage V_2, while $V_2<V_1$. The flow rate of a dense flow decreases with a power law, $Q\sim V^{-\beta}$ and, here, $\beta=1$. These observed dilute and dense transitions at different voltages are similar to a first-order phase transition in equilibrium systems. The flow rate of the dilute flow is higher than that of the dense flow, and the existence of the critical density or critical voltage that a transition between dense and dilute flow occurs shares similarities to the traffic flow.[10] A two-dimensional molecular dynamics (MD) simulation is performed and the results agree qualitatively well with the experimental observations.

The experimental setup is similar to that described in our previous papers.[8,9] In the experiment, nickel spheres of average diameter $d=0.25$ mm are used. (Other particles such as glass beads and steel balls have also been used and give qualitatively similar results.) The vertical pipe is of 10 cm in length, with inner diameter $D=3$ mm. Two 1.5 cm$\times$1.2 cm rectangular copper electrode plates, separated by 4.4 mm, are attached to the pipe with their upper ends of a distance L of 6.5 cm from the bottom of the pipe.

In the first sequence of our experiments, the flow is initiated after V is set at a fixed value (from 0 V to 4.8 kV, at an interval of 0.2 kV). The recorded total mass coming out of

[a]Electronic mail: cwei@aphy.iphy.ac.cn
[b]Also at: Department of Applied Physics, Harbin Institute of Technology, Harbin 150001, China.
[c]Also at: Nonlinear Physics Group, Department of Physics, San Jose State University, San Jose, CA 95192-0106.

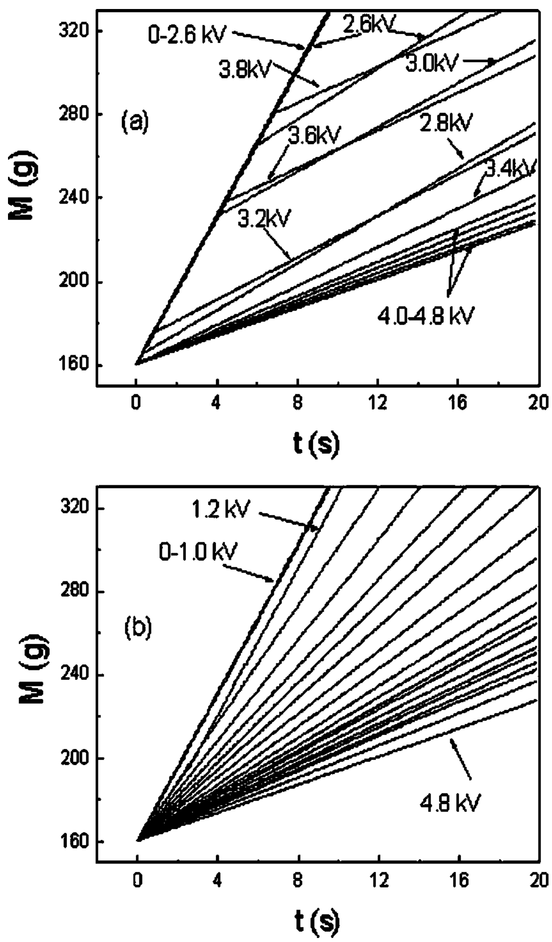

FIG. 1. Mass recorded as a function of time t at each different voltage V: (a) prepared in sequence I (initially dilute); (b) in sequence II (initially dense).

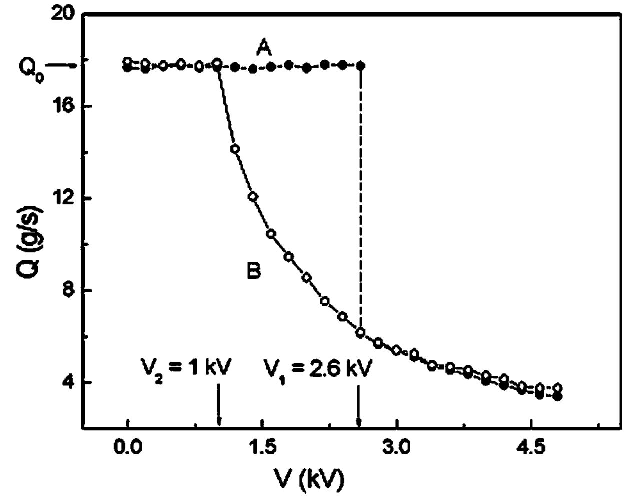

FIG. 2. Dependence of flow rate Q on the applied voltage V. The solid (open) dots represent the data points obtained from the first (second) sequence experiments. The curved solid line is fitted by $Q=16.9\,V^{-1}$. The horizontal and vertical lines are drawn to guide the eye.

the pipe M as a function of time (t) at each V is shown in Fig. 1(a). Below 2.6 kV, the flow is at one constant rate. Above 2.6 kV, the flow deviates from the initial rate into a slower constant rate.

The procedure of our second sequence experiments is the same as the first sequence, except that V is first fixed at 4.8 kV; the flow is initiated and reaches a steady state; then, V is decreased to the desired, fixed voltage (from 4.8 kV to 0 V, at an interval of 0.2 kV). The $M(t)$ curve at each V is recorded as shown in Fig. 1(b). It is noticed in Fig. 1(b) that the $M(t)$ curves overlap in the range $0 \leqslant V \leqslant 1.0$ kV, a range different from the first sequence.

The flow rate $Q(t)$ obtained from the steady-state slopes of the $M(t)$ curves is plotted against V in Fig. 2. In the first sequence, $Q(V)$ is practically at a constant value Q_0 before V reaches V_1 $(=2.6\,\text{kV})$. At V_1, Q drops abruptly by an amount ΔQ; Q then decreases gradually as V increases further. The $Q(V)$ curve from the second sequence agrees well with that of the first sequence, except for the region of $V_2 < V < V_1$, where $V_2 = 1.0$ kV. The voltage V_2 is a continuous transition point at which Q changes from a dense flow ($V > V_2$) to a dilute flow ($V < V_2$).

Video images of the flow at different V are shown in Fig. 3. The exposure time of each picture is 0.5 ms. At $V=0$ kV, the blurred image of particles entering the electrode region, as seen in Fig. 3(a), shows that particles move about 0.5 mm within the exposure time. (Each line of the ruler in the picture marks 1 mm.) At $V=2.6$ kV, flow is retarded by the electric field and becomes dense and slow so that each particle, as shown in Fig. 3(b), can be identified clearly within the exposure time. As V goes higher [Fig. 3(c)], at $V=4.8$ kV, an interface appears at the top of the electrode region, above which a dense region exists, and below which particle density becomes dilute. The intermittent arch induced by the electric field can be viewed clearly at this voltage.

The effect of the dipole interaction induced by the electric field acting on the particles can be explained as follows. The insulated particles are polarized in the electric field. The induced dipole can be written as $\mathbf{p}=4\pi\epsilon_0 R^3 \mathbf{E}$, where R is the radius of the particles. Considering dipole interaction, the force $\mathbf{f}$ acting on the polarized particle in an inhomogeneous electric field $\mathbf{E}$ can be expressed as

$$\mathbf{f} = -\nabla(-\mathbf{p}\cdot\mathbf{E}) = 4\pi\epsilon_0 R^3 \nabla E^2. \tag{1}$$

When the interaction is comparable to the kinetic energy of the falling particles, particles will be dragged by the gradient of the field and converge to the sidewalls near the top of the electrodes. This force against the wall induces a friction between the particle and the wall, which reduces the velocity of particles along the wall. The interaction between polarized particles attracts particles moving closer to each other, and enlarges the local field between particles. En-

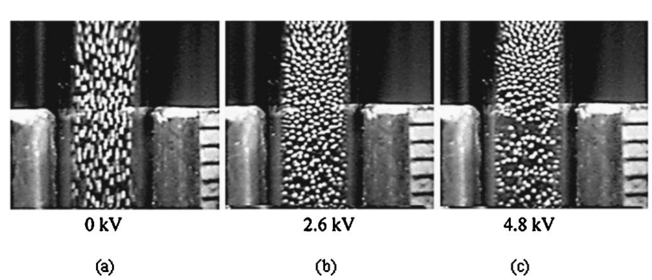

FIG. 3. Photographs of granular flow entering the electric field at different V. (a) $V=0$ V, (b) $V=2.6$ kV, and (c) $V=4.8$ kV. The electrodes are at the lower half of each picture. The lines on the right-hand side of each photograph are 1 mm apart.

hancement of the local field between particles then further increases their mutual induction and causes particles to further aggregate. This positive-feedback effect, we believe, is the major contribution that causes the flow rate to drop abruptly at V_1. An estimated critical voltage gives a threshold $E_c = 7\times10^5$ V/m, which corresponds to a voltage ≈ 3.1 kV. It is of the same order of magnitude but higher than V_1 due to the simple dipole approximation.

A simplified model is used to elucidate why the flow rates keep constant for dilute flow before the critical voltage. In this model only the column of particles next to the wall are considered. For simplicity, we assume, before entering the electric field, particles move with a constant velocity v_1, and the distance between adjacent particles to be s_1. The initial flow rate can be written as $Q_0 \sim v_1/s_1$. After particles enter the field, the particle velocity is changed to v_2 ($<v_1$, due to the retarding effect of the electric field). Velocity v_2 is a function of the local electric field E_L acting on each particle, which is proportional to V, i.e., $E_L \propto V$. We assume $v_2 \sim v_1 E_L^{-\alpha}$, where α is a positive number. The distance of particles in the field is changed to s_2, with $s_2 = (s_1 v_2)/v_1$. Therefore, $s_2 \sim s_1 V^{-\alpha}$.

Since s_2 cannot be smaller than the diameter of particle d by its definition, s_2 shall not decrease unlimitedly as V increases. We thus define the voltage, at which $s_2 = d$, to be the critical voltage V_c. From the above equation and at $s_2 = d$, V_c can be obtained $V_c \sim (s_1/d)^{1/\alpha}$. Note that $Q \sim v_2/s_2$ and from above equations, we then obtain $Q = Q_0$ when $V < V_c$, and

$$Q \propto V^{-\alpha}, \tag{2}$$

when $V > V_c$. When $V < V_c$, the slowdown of the particles in the field is accompanied by an increase of the particle density, and makes the flow rate invariant with V. When $V > V_c$ ($s_2 = d$), the particle density reaches a maximum, and the slowdown of particles reduces the flow rate directly.

For a real system, we need to take multicolumn particle interaction into account, i.e., to add the influence of the induced interparticle interaction on E_L, which means $s_2 \sim E_L^{-\alpha}(s_2)$. The decrease of the distance between particles along the electric-field lines will increase E_L. The increase of this attractive interaction will further decrease particle separation s_2. Therefore, a positive-feedback mechanism of E_L vs s_2 exists after particles enter the electrode area. When V is low, this mechanism is weak. Particles will flow out of the field before they are able to stick to each other (when $s_2 = d$), and the steady-state flow rate Q will not change. As V increases to the critical voltage V_1, the separation s_2 will be close enough to d to change the local electric field dramatically. Therefore, particles will stick to each other and a sudden drop in the flow rate Q occurs.

In the second sequence of experiments, the flow is initiated to reach a dense flow. As we decrease voltage V, particle velocity v_2 increases with the bulk density of the particles unchanged. Therefore, as V decreases flow rate Q increases monotonically with no sudden jump, as is also indicated by Eq. (2). There should be a cutoff voltage V_2, at which $Q(V_2) = Q_0$. Q_0 is the maximum flow rate in the pipe, which is determined by the inflow rate. Since Q_0 is fixed, the cutoff voltage V_2 will be fixed, too. Below voltage V_2 flow rate $Q(V)$ shall always be Q_0.

A two-dimensional computer simulation based on the MD method, in which the interaction, collisions, and friction between polarized particles and between the particle and the wall, as well as the gravitational force were taken into account. The simulation results on the distribution of particles in the pipe are comparable with the experimental observation. The simulated behavior of Q vs V is consistent qualitatively with the experimental measurements. The simulated results will be published later.

In conclusion, a local, horizontal ac electric field is shown to be able to retard the granular flow of nickel particles in a vertical pipe. Particles converge and aggregate near the top of the electrodes. These aggregations, due to electric-field-enhanced friction effect, slide down slowly along the inner sidewalls near the electrodes. The Q vs V curve shows two transitions exist, one from dilute to dense, which occurs at a voltage V_1. At this voltage, there exists a sudden drop of Q. The transition from dense to dilute occurs at a voltage V_2; V_2 is always smaller than V_1, and no sudden change in Q was observed. The positive-feedback process in the granular system induced by electric field is discussed. A simplified model is able to explain the important features observed in our experiments. The agreement between the computer simulation and the experiment also suggests the validity of our model.

This research is supported by the State Key Program for Basic Research of China and the Chinese National Natural Science Foundation.

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