Granular flows through vertical pipes controlled by an electric field

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I. INTRODUCTION

Granular matter is a subject of intense interest [1–5] in recent years. In this field, many important topics in nonlinear physics [6]—such as pattern formation [5], solitons [7], chaos [8], and cellular automata [9–11]—were studied. In particular, nonlinear waves in granular flow have been observed and computationally simulated [12–19].

This discrete, compressible system has distinct features when compared with classical fluids. Density fluctuation is an important character of granular flow and has been broadly noticed. Many interesting phenomena related to it were observed in different experiments using x-ray imaging [19], spatiotemporal diagrams [14], and light detector [15]. Intermittent and kinematic shock wave [12] was found in a small-angle two-dimensional funnel when the funnel angle was changed. Different kinds of wave regimes [14] in the vertical pipe were observed when the mass-flow rate was changed by adjusting the stopcock at the bottom end of the tube. The power spectra of density waves were shown to assume a power-law form, when the air outflow rate was changed. Different kinds of wave regimes [14] in a two-dimensional hopper were observed when the mass-flow rate was changed by applying a local, ac electric field—is introduced to study the nickel particle flow in a vertical pipe attached to a hopper. Different density patterns in the flow were observed at different electric-field strengths. Due to the dipole-dipole interaction induced by the electric field, particle clusters were formed near the field and the granular flow rate was reduced nonlinearly with the applied voltage.

II. EXPERIMENTAL SETUP AND METHOD

A hopper with open angle 60° is joined to a short tube of 9 cm long with inner diameter of 7 mm. The tube is then joined to a long pipe of length 85 cm and inner diameter 3 mm. The vertical length between the tube and the pipe is 1 cm (see Fig. 1). All these parts are made of glass. The presence of the short tube practically prevents the flow rate in the pipe from being influenced by how particles are piled up in the hopper.

Most of the particles are spherical in shape (of average diameter 0.25 mm). The nickel particles are metallic; however, they are covered with a thin film of oxide after exposed in air for a long time. The particles are thus electrically insulated from each other.

Two copper electrode plates of vertical length 10 cm, and 1.2 cm in width, are fixed upon the outside wall of the long pipe. The distance between the two electrodes is 5 mm, which is equal to the outer diameter of the long pipe. The upper ends of the electrodes are at a distance of 60 cm from the top of the pipe (see Fig. 1). An ac electric voltage V of 50 Hz in frequency is applied across the electrodes.
In our experiments, the applied voltage $V$ is fixed in a range of 0–6 kV. The voltage $V$ is increased by 0.2 kV for each different run. For each fixed voltage $V$ applied across the two electrodes, the total mass on the balance $M$ is measured as a function of time $t$.

Since nickel is a weak ferromagnetic element, we have used a magnet as a stopper to block or initiate the flow. In fact, an electromagnet placed 1 cm above the bottom end of the pipe, outside of and in contact with the glass pipe, is used. In the beginning of the experiment, we turn on the control current of the electromagnet. We then fill the hopper and the pipe with the nickel particles, up to a fixed height in the hopper. The magnet keeps the particle column from falling out of the pipe. When the control current is switched off, the particles fall down from the pipe and are collected in a container placed on an electronic balance. A thin layer of nickel particles is initially placed inside the container to absorb the impact of the falling masses. The balance sends data to a personal computer at a time interval of 0.4 sec. The resolution of the balance is $10^{-3}$ g, and the maximum mass allowed by the balance is 200 g.

During the experiments, the humidity is maintained at 47–55%. This is one of our efforts to reduce the static electric caused by low humidity and, at the same time, to prevent the formation of particle aggregations due to high humidity.

**III. EXPERIMENTAL RESULTS**

For each experimental run, the mass $M$ collected by the electronic balance as a function of time $t$ is given in Fig. 2. At time $t = t_0$, the measured mass of 40 g is the total mass of the container and the initial thin layer of particles placed there. After the flow reaches the balance, the recorded mass $M$ increases with time. At a different voltage the slope of the recorded mass vs time curve is different, as can be easily seen in Fig. 2. The lower the voltage, the faster the flow. It is an immediate evidence that the application of an external electric field is able to affect and retard the granular flow.

The flow rate $Q (=dM/dt)$, as a function of $t$, is obtained from the slope of the $M(t)$ curve, and is plotted in Fig. 3 with $V$ as a parameter. For viewing convenience, each $Q(t)$ curve at different voltage has been shifted vertically upward by 10 g/s from the one below it. When the voltage is zero, the flow rate increases from zero rapidly and fluctuates for a

![FIG. 1. Sketch of apparatus.](image)

![FIG. 2. Dependence of mass $M$ on time $t$. The voltage difference between two adjacent curves is 0.2 kV.](image)

![FIG. 3. Steady-state flow rate $Q(t)$, obtained from the slope of $M(t)$ at large $t$ in Fig. 2. For viewing convenience, each of the curves with $V \geqslant 0.4$ kV has been shifted upward by 10 g/s from the curve below it. Each horizontal line represents $Q = 5$ g/s, and is drawn to guide the eye to show that $Q_B$ does not change, while $Q_A$ decreases with voltage. A dotted line connects all the second peaks separating regime A from regime B in the $Q(t)$ curves.](image)
few seconds before it goes steady. As the field is increased, the fluctuating part of the curve expands and eventually separates into two distinct peaks at about $V=1.4$ kV. The first peak stays at the same location, while the second peak moves to the right when $V$ is increased. At $V \geq 2.0$ kV, the second peak disappears (see Sec. IV for an explanation). At the same time, the constant flow rate beyond the first peak decreases continuously as $V$ increases, as is shown in Fig. 3.

IV. DISCUSSION

A. Time dependence of the flow rates

As shown in Fig. 3 and sketched in Fig. 4(a), the time-dependent flow rate $Q(t)$ curve can be separated into three regimes $A_1$, $A_2$, and $B$. The time location of the first peak is called $t_1$; the one for the second peak is called $t_2$. Regime $A_1$ is defined as the time interval between $t=0$ and $t=t_1$, regime $A_2$ as the part between $t_1$ and $t_2$, and regime $B$ the part beyond $t_2$. At $V < 1.4$ kV (see curves in Fig. 3), the second peak is too close to the first peak, so that the two peaks can hardly be distinguished. Thus, regime $A_2$ is buried in the fluctuation of the two partly overlapped peaks and $Q_{A_2}$ is thus not measurable. (Here, $Q_{A_2}$ is defined as the $Q$ at the middle point between $t_1$ and $t_2$.) For these curves, regime $B$ is the only regime where a measurable rate—the “flat” (steady) part of the $Q(V)$ curve—may be obtained. On the other hand, for $V > 1.8$ kV only one peak remains; the “flat” part corresponds to the flow rate in regime $A_2$. There is no regime $B$ since the second peak no longer exists. Only in the intermediate $V$ range ($1.4$ kV $\leq V \leq 1.8$ kV), flow rates in both regimes $A_2$ and $B$ are measurable.

The three regimes described above may be understood as follows. In our experiments, the hopper and the pipe above the stopper are filled with nickel particles before the flow is initiated at time $t=t_0$, as shown in Fig. 4(b) by the dark gray color. Particles in this system may be separated into three regions according to their initial location: (i) particles in the pipe below the electrodes, (ii) particles in the pipe above the electrodes, and (iii) particles in the hopper. These three regimes can be imagined to be separated by two layers of particles, which are called layer $a$ and layer $b$, respectively [see Fig. 4(b)]. Particles in these three regimes flow at different rates. The location of layer $a$ is within and slightly below the top end of the electrodes; below layer $a$, the effect of the electrodes is practically zero or can be ignored. Layer $b$ is at the top of the pipe. Particles in region (i) flow solely under gravitational force. Particles in region (ii) are retarded by the electric field, and thus move down slower than particles in region (i). Particles in region (iii) flow into the pipe at a rate determined by the hopper outlet. Due to these rate differences, as layer $a$ reaches the balance at time $t_1$, layer $b$ moves downward and reaches somewhere above the electrodes. Layer $b$ actually becomes an interface with particle density above it lower than that below it. Simultaneously, an interface appears at the original location of layer $a$, with particle density from above denser than that at below, opposite to the case at layer $b$. (Here and below, in reality, the interface is a region of varying density and is of finite width.)
But for simplicity of drawing, it is represented by a sharp line.

The flow rate increases from $Q(t_0) = 0$ rapidly until layer $a$ reaches the weighing balance at time $t_1$, as is shown in Fig. 4(c). From time $t_0$ to $t_1$, defined as time regime $A_1$, particles in the flow come from region (i); the flow is affected neither by the electric-field blocking effect nor by the hopper outlet pushing effect.

In between time $t_1$ and $t_2$ (regime $A_2$), an interface $b$ is observed, which moves from top part of the pipe to reach the weighing balance at $t_2$. The steady-state flow rate $Q_{A_2}$ is always lower than $Q_{A_1}(t_1)$ due to the retardation effect of the electric field. Therefore, there exists a peak at $t_1$. The particles flowing at the rate $Q_{A_2}$ come from region (ii). It is a “dense” flow, in the sense that the flow comes from a dense column of particles from above the electrodes. Note that in this case, this dense column situates right below a dilute column [see Fig. 4(c)].

At time $t_2$, particles at the interface $b$ reach the weighing balance shown in Fig. 4(d). Beyond time $t_2$, the weighing balance begins to record mass of particles initially from region (iii). The flow then reaches a steady-state rate $Q_{B}$. This flow is called a “dilute” flow, in the sense that the flow comes from a column of dilute particles in the pipe below the hopper. (Both $Q_{A_2}$ and $Q_{B}$ actually measure the flow rate out of the bottom of the electrode region, since the original particles in region (i) below the electrodes flow out already in regime $A_1$.)

The rising part of the second peak of the flow rate $Q_{A_2}$ near time $t_2$ is due to the finite width of the interface $b$. In this transition region, particle density varies gradually from dense (below the interface $b$) to dilute (above the interface $b$). The flow retardation effect caused by the electric field is reduced as the flow gets more dilute. Thus, as the interface $b$ passes through the electrodes, the measured flow rate $Q_{A_2}$ increases.

**B. Critical voltage and the second peak**

There are two peaks in the $Q(t)$ curve in Fig. 3. The time location of the second peak $t_2$ increases as voltage $V$ increases. The location of the first (second) peak corresponds to the time that layer $a$ (layer/interface $b$) reaches the balance.

The downward-moving velocity $v_b$ of interface $b$ in the pipe is roughly proportional to the inverse of $\Delta t$ ($=t_2-t_0$). From the location of $t_2$ for each $V$ in Fig. 3, $\Delta t$ vs $V$ is obtained and plotted in Fig. 5, which is a straight line and vanishes at $V = V_c = 2.0 \pm 0.1$ kV. At the critical voltage $V_c$, $\Delta t \to \infty$, indicating that the second peak in the $Q(t)$ curve no longer exists, as confirmed by Fig. 3. Physically, for $V \geq V_c$, the electric field is strong enough to retard the flow coming from above the electrodes so that the density above layer $b$ is the same as that below the layer; a dense column appears above the electrodes. In other words, even though layer $b$ indeed moves downward, it no longer becomes an interface as in the case of $V < V_c$.
C. Dependence of the flow rates upon electric voltage

The flow rates $Q_{A_2}$ and $Q_B$ measured from Fig. 3, as a function of $V$, are plotted in Fig. 7(a). As shown in Fig. 4(d), particles initially in region (iii) (particles in the hopper) flow through the pipe and reach the balance at a rate $Q_B$. The flow rate $Q_B$ appears and is measurable only below the critical voltage 2.0 kV (see Fig. 3). From Fig. 7(a), $Q_B$ is apparently independent of $V$. The flow rate $Q_{A_2}$, however, appears and is measurable at all voltages as long as the two peaks in the $Q(t)$ curve are distinguishable. $Q_{A_2}$ is the rate of particles coming from region (ii) (particles in the pipe), as measured at the balance. As shown in Fig. 7(a), $Q_{A_2}$ is voltage dependent; it decreases monotonically with $V$. While the horizontal $Q_B$ curve terminates abruptly at $V=2.0$ kV, there is no physical reason that the $Q_{A_2}$ curve cannot be extended to the low $V$ region. What is needed is better resolution in the $Q(t)$ curve in Fig. 3.

The two curves $Q_{A_2}$ and $Q_B$ cross each other at a voltage $V_0\approx 1.6$ kV. What happens physically near $V_0$ is very interesting. By definition, $Q_{A_2}$ precedes $Q_B$ in time in the measurement. The fact that $Q_{A_2}>Q_B$ at $V=1.4$ kV is not surprising, since what it implies is that the flow rate out of the hopper is lower than that out of the pipe, consistent with the picture that there exists an interface $b$ [see Fig. 4(c)]. What is surprising is that at $V=1.6$ and $1.8$ kV, respectively, $Q_{A_2}<Q_B$ is recorded. The lowering of $Q_{A_2}$ at these two voltages implies that the voltage is large enough to retard the dense column of particles in region (ii). The paradox arises from the fact that if $Q_B$ is greater than $Q_{A_2}$, then how come an interface $b$ with dilute particles above it) can exist, if $Q_B$ is interpreted as the flow rate out of the hopper outlet? The answer to this puzzle rests on the fact that during the flow when $Q_{A_2}$ is measured, the flow rate out of the hopper is not $Q_B$, but $Q_{B'}$. $Q_{B'}$ is lower than $Q_B$ because of the air trapped above the interface $b$; the air will tend to slow down the particles falling out of the hopper. This air effect is more prominent for $V$ less than but close to $V_c$, because particles flowing out of the hopper see a hardly moving interface $b$, i.e., $v_b=0$. A log-log plot of $Q_{A_2}$ vs $V$ is given in Fig. 7(b), giving a power law of $Q_{A_2}\sim V^{-0.8}$.
V. CONCLUSION

The influence of ac electric voltages on the flow of nickel particles from a hopper into a vertical pipe is studied. The applied horizontal electric field is shown to be able to retard the granular flow. The flow rate is controlled at two vertical positions: at the hopper outlet and near the upper end of the electrodes. Three flow rate regimes $A_1$, $A_2$, and $B$ are observed and explained. At relatively weak electric fields when $V < V_c$ ($= 2.0$ kV), a transition of the granular flow in the pipe from regime $A$ to regime $B$ is observed. The higher $V$ is, the longer regime $A_2$ lasts. When $V > V_c$, regime $B$ of the flow disappears and the flow stays in regime $A_2$. The flow rate at regime $B$, $Q_B$, is practically unaffected by $V$. The flow rate of regime $A_2$, $Q_{A_2}$, decreases with $V$ monotonically with a power law, which shows that the applied electric field can indeed retard the nickel granular flow. At voltage $V_0$ slightly below $V_c$, $Q_{A_2}$ equals to $Q_B$. Air column effect is believed to be important near $V_0$.

The retardation effect of the electric field may be attributed to particles forming clusters at the two sidewalls near the electrodes, when $V$ is large enough. Due to the inhomogeneity of the electric field, the polarized particles are pulled towards the two sidewalls; the friction between the particles and the walls is enhanced. The clusters near the wall block the movement of some particles and effectively reduces the cross-sectional area of the tube at the electrode region, resulting in retardation in the flow.

The flow features are explained as coming from a competition between the blocking effect due to the electric field and the pushing effect due to gravity. Note that the whole pipe is saturated with dense particles initially. In regime $A_2$, the local electric field is able to retard the downward movement of the dense column of particles above it; this flow is called a “dense” flow. Within this regime, depending on the magnitude of $V$, two kinds of behaviors are observed. (i) For $V < V_c$, the flow rate from the hopper outlet is less than that below the electrode region; a dilute column exists right below the hopper outlet. As time increases, this column extends in length from zero to throughout the whole pipe. The flow becomes a “dilute” flow—this is regime $B$. The voltage $V (< 2.0$ kV) is not able to retard this dilute flow in regime $B$, because the particles are not close enough to each other that the induced dipole interaction is too weak to bind the particles together to form clusters. (ii) For $V > V_c$, the flow rate below the electrodes decreases so much (compared to that from the hopper outlet) that a dilute column below the hopper is never formed, leading to the absence of regime $B$. The flow in regime $A_2$, a dense flow, is retarded by the electric field, as in case (i).

An interesting question remains on whether a high enough voltage exists that is able to retard a dilute flow. Within our experiments reported here, this question cannot be answered. The reason is that because the pipe is initially densely filled due to the placement of the switch at the bottom of the pipe, a dilute flow does not exist for $V > 2.0$ kV. Therefore, we cannot test the effect of $V$ on a dilute flow here, for $V > 2.0$ kV. In fact, in a separate experiment in which dilute flows are created by effectively placing the switch right under the hopper [22], the dilute flow is retarded by high enough voltages.

ACKNOWLEDGMENTS

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