Reverse Ordering in Dynamical Two-Dimensional Hopper Flow

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Abstract

We study the exit ordering of grains in gravity driven flow through two-dimensional hoppers of different hopper angle and outlet size with adjustable reclining angle. We observe a reverse ordering phenomenon such that grains entering the hopper at earlier times may not come out earlier. We record the entry order and exit order of the grains and calculate the degree of reverse ordering which is found to increase with increasing hopper angle, decreasing reclining angle, and increasing hopper outlet size. In order to find the mechanism of reverse ordering, we construct maps which register the entry order and exit order according to the position of the grain in the hopper before the flow. By comparing the exit order map and the entry order map we locate the regions where grains undergo reverse ordering. From the trajectories of the grains in the reverse ordering regions, we find that they take part in avalanches at the surface on their way to the exit. Hence, it is the dynamical process of surface avalanche that reverse the exit order of the grain when they flow out of the hopper. These results may be useful for special hopper design in agricultural and pharmaceutical industries to reduce or to enhance reverse ordering of materials for specific purposes.

Introduction

Physical parameters

Plastic spheres (diameter = 6mm; BB bullets) are used in this study. We constructed 2D hoppers made of acrylic plates with different hopper angle θ (30°~60°) and reclining angle φ (15°~90°).

Methods

We load grains into the hopper by a 2D channel. After we open the gate, grains will flow out of the hopper. The whole process is recorded by a high speed camera at 300fps.

Theoretical background

Trough the high speed camera and programs, we can obtain the entry order I and the exit order O of each grain.

$$\gamma_i = I_i - O_i$$

$$\Gamma = \frac{1}{f(N)}\sqrt{\sum_{i=1}^{N}\gamma_i^2}$$

$$f(N) = \sqrt{\frac{N^3 - N}{3}}$$

We define two quantities— (1)γ_i, which denotes the order difference of each grain i, and (2)Γ, which represents the degree of reverse ordering of an experiment and ranges 0 to 1. A larger Γ represents a larger degree of reverse ordering.

I_i: entry order of grain i N: number of grains

O_i: exit order of grain i $f(N)$: normalizing factor

Result and Discussion

Maps of grains' order

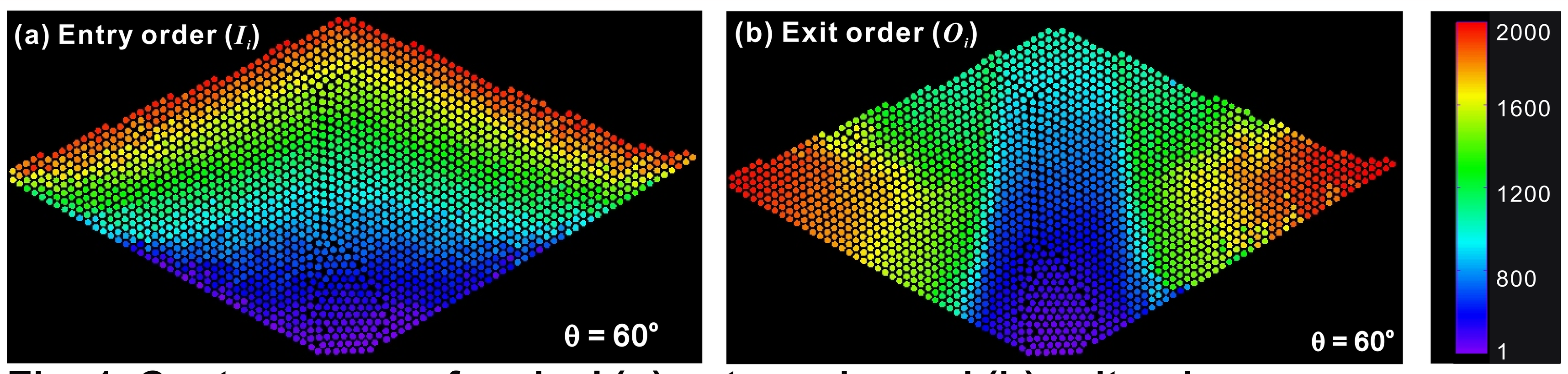

Fig. 1 Contour maps of grains' (a) entry order and (b) exit order

We draw maps of grains' entry order (Fig. 1(a)) and exit order (Fig. 1(b)) according to the grains' initial locations in the hopper before they flow out. In the map of entry order, the grains with similar colors will enter the hopper together. The map looks stratified horizontally, means that grains do not mix seriously when entering the hopper (Fig. 1(a)). In the map of exit order, the grains with similar colors will exit the hopper together. The map looks stratified vertically (Fig. 1(b)), which is different from the map of entry order.

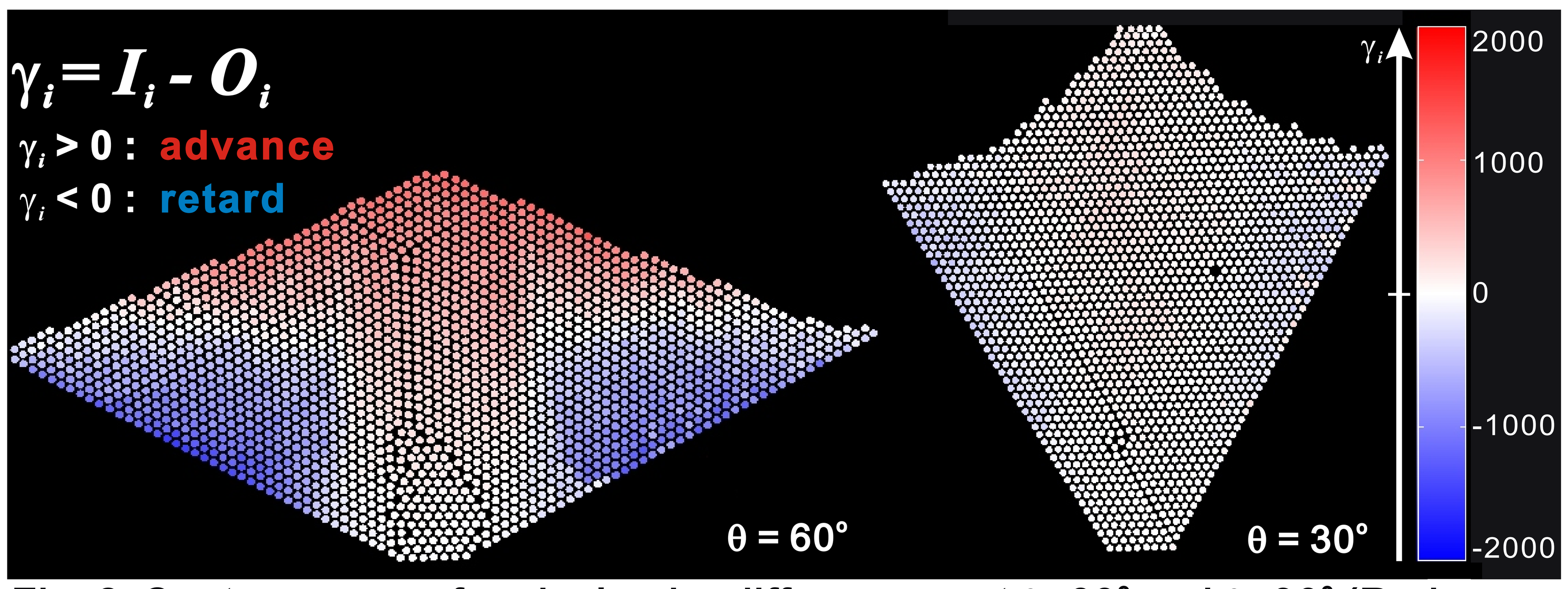

Fig. 2 Contour maps of grains' order difference γ_i at θ=60° and θ=30° (Red grains: advance; blue grains: retard)

To find out the regions that grains undergo reverse ordering, we draw maps of the order difference γ_i (Fig. 2). The grains initially located at the central part and the side-wall part of the hopper undergo reverse ordering.The colors at θ=30° are lighter than the colors at θ=60°. Hence, this indicates that the degree of reverse ordering of the former is smaller than that of the latter.

Discussion

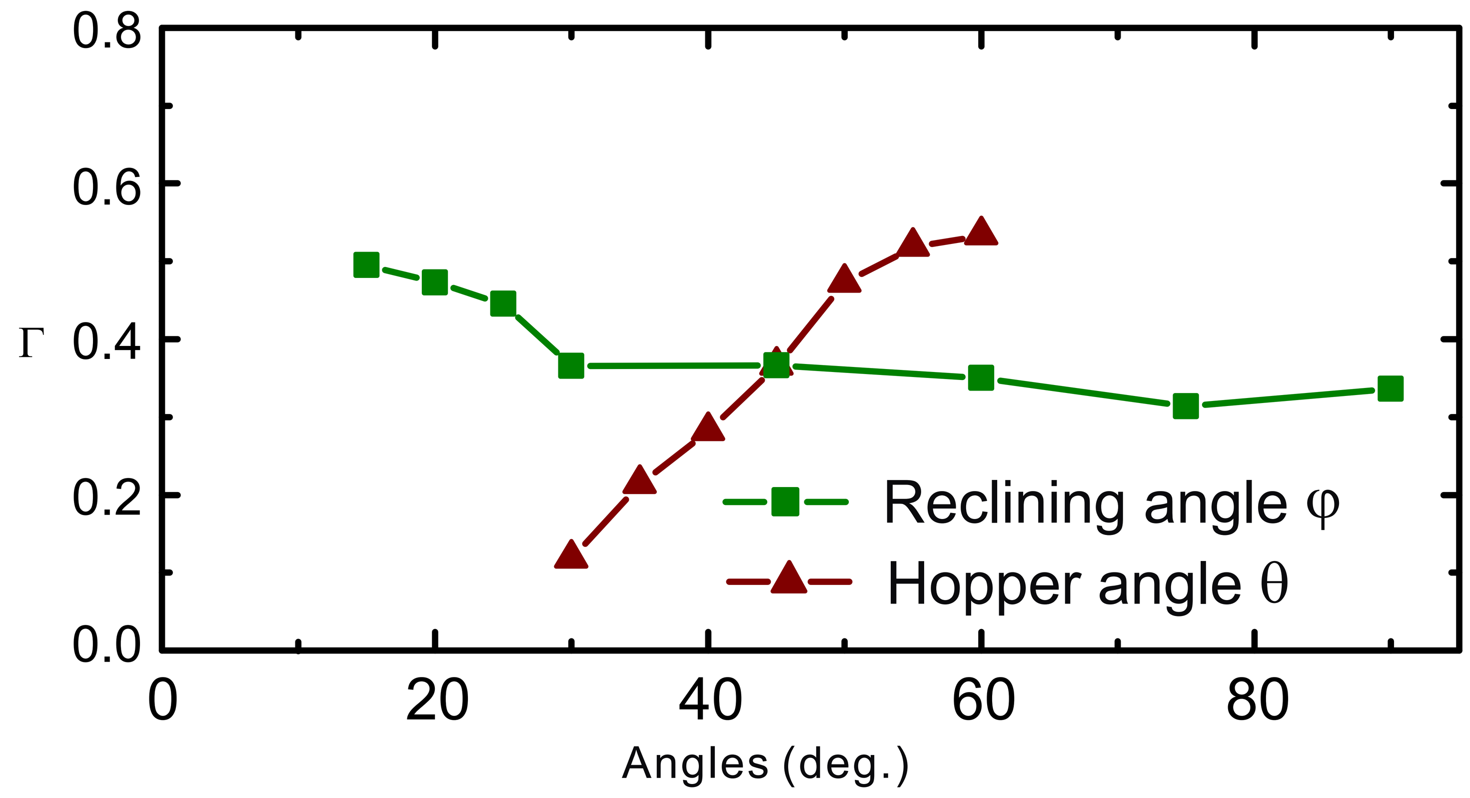

Fig. 3 Effects on the degree of reverse ordering Γ of different parameters

The degree of reverse ordering Γ increases with decreasing reclining angle φ and increasing hopper angle θ (Fig. 3). A larger reclining angle φ speeds up the flow and reduces the completion time difference between central flow and side-wall flow, which reduces the degree of reverse ordering. A larger hopper angle θ provides a larger frictional force for a grain on side wall, and this slows down side-wall flow and increases the completion time difference, which increases the degree of reverse ordering.

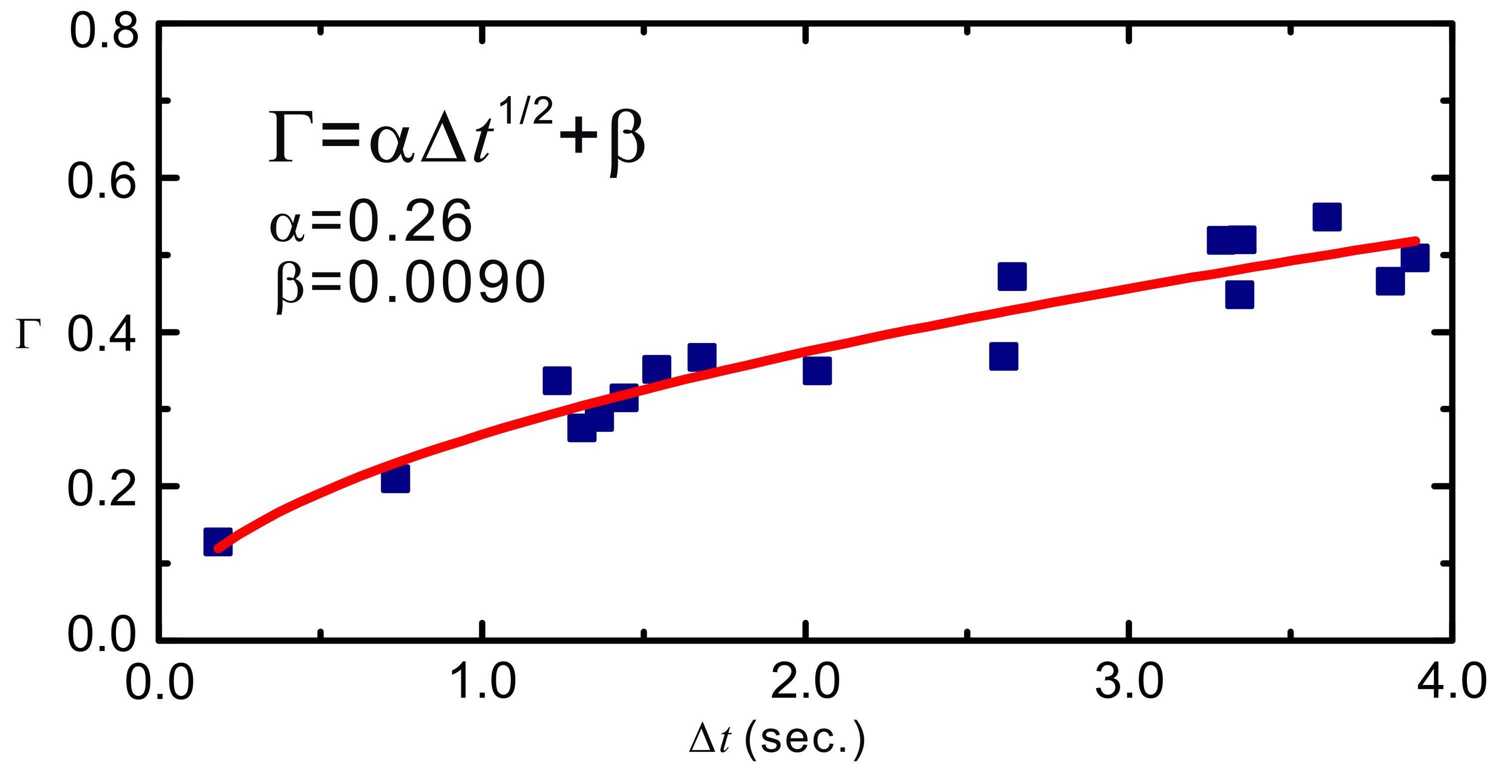

Fig. 4 Dependence of the completion time difference Δt between central flow and side-wall flow on the degree of reverse ordering Γ

We think a larger degree of reverse ordering Γ results from a larger completion time difference between central flow and side-wall flow. To check our theory, we measured the completion time for central flow (t_c) and side-wall flow (t_s) and calculated their difference Δt (t_s-t_c). The degree of reverse ordering Γ is proportional to the square root of the completion time difference $\Delta t^{1/2}$ (Fig. 4).

Applications

These results may be useful for special hopper design in agricultural and pharmaceutical industries. The reverse ordering may influence the dropping order of grains while packing or transporting, making them spoil and stranded, even affect the freshness of the items such as millet, medicines, and ores.

Conclusions

1. A reverse ordering phenomenon is observed.
2. Grains start from the central part of the hopper will advance while those start from the side-wall part of the hopper will retard.
3. Macroscopically, the degree of reverse ordering can be quantified by Γ, the quantity we defined, which is sensitive to the hopper angle.
4. The completion time difference Δt between central flow and side-wall flow, which is a mesoscopic property, leads to the reverse ordering of grains, and Γ is proportional to $\Delta t^{1/2}$.
5. Microscopically, grains undergo avalanches at the surface of the flow, which also influences the reverse ordering.

References and acknowledgments

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