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Dense Inclined Flows: Theory and Experiments
Quarterly Technical Progress Report (April 1, 1994 to June 30, 1994)

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Summary of accomplishments

Rapid, gravity-driven flows of granular materials down inclines pose a challenge to our understanding. Even in situations in which the flow is steady and two-dimensional, the details of how momentum and energy are balanced within the flow and at the bottom boundary are not well understood. Thus we have undertaken a research program integrating theory, computer simulation, and experiment that will focus on dense entry flows down inclines. The effort involves the development of theory informed by the results of simultaneous computer simulations and the construction, instrumentation, and use of an experimental facility in which the variables necessary to assess the success or failure of the theory can be measured.

In the present reporting period, we have completed improvements of the chute and we have demonstrated the three new instruments incorporated in the facility (capacitance, impact and microphone probes). In addition, using computer simulations of rapid granular flows, we have refined our theoretical predictions of the flux of fluctuating energy through a flat, frictional wall.

1. Instrumentation

We have acquired signals from all new instruments incorporated in the chute facility. The capacitance probe provides the time dependent concentration near the bottom wall. By recording the collision frequency of particles with a thin rod, the microphone probe provides an objective determination of the free surface of the flow (Fig. 1).

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Fig. 1. Collisional count of the microphone probe vs. height above the chute for typical conditions.

The impact probe records individual impacts on a small rod mounted flush with the chute surface. Because the diameter of the rod is equal to that of the spheres, only one sphere impacts the rod at a time. A typical signal for this probe is shown in Fig. 2. The first peak voltage is related to the peak normal force during the impact. A calibration permits to relate this voltage with the normal velocity at impact. A statistical analysis of successive events provides the normal component of the granular temperature at the wall.

Fig. 2. Typical impact of a sphere on the rod.

2. Measurements of Particle Properties

In this reporting period, we have prepared ourselves to incorporate the Kodak DCS camera in the impact experiment. The next step is to record the collision properties of the glass beads used in the experiments.

3. Theory and Computer Simulations

We have further refined our calculations of the flux of fluctuating energy through a flat, frictional wall. We have interrogated computer simulations to determine why our predictions for the flux differed from the results of the simulations in the limit of large sliding. In particular, we have found that the flux in the "all-sliding" limit has an additional term shown in curly brackets,

$$Q = -M \cdot g_0 - D = \frac{1}{2} m \left[\frac{2}{7} \mu_0^2 - (1-e^2) \right] F[g_n^2] + \frac{2}{7} m \mu_0 \{ F[|g_t| g_n] - F[g_n t] \cdot g_0 \}, \quad (1)$$

where $F[\psi]$ is the property ψ of the spheres impacting the wall per unit area of the wall and per unit time,

$$F[\psi] \equiv -\chi \int_{c \cdot n \leq 0} \int \psi f(c, \omega) c \cdot n \, dc \, d\omega,$$

$g_t \equiv g \cdot t$ and $g_n \equiv g \cdot n$. A calculation shows that the new term in curly brackets is approximately equal to the correlation

$$\{ F[|g_t| g_n] - F[g_n t] \cdot g_0 \} \approx F[G \cdot x G \cdot n], \quad (2)$$

where G is the fluctuating component of the relative velocity g of the contact point with the wall and x is the vector in the direction of the mean flow. The correlation $F[G \cdot x g \cdot n]$ may be estimated by considering the elementary change in the fluctuating component of g through a single collision with the wall. Consider a sphere impacting the wall with the contact velocity $g + G$. The post-impact velocities are given by

$$g^* - g = \frac{7}{2m} J - \frac{5}{2m} n (J \cdot n), \quad (3)$$

and, because (3) and J are linear,

$$G^* - G = \frac{7}{2m} \Delta J - \frac{5}{2m} n (\Delta J \cdot n), \quad (4)$$

where ΔJ is the incremental impulse caused by the fluctuation G . Therefore in the "all sliding" limit,

$$G^* - G = -(1+e) (G.n) n + \frac{7}{2}\mu(1+e) (G.n) t. \quad (5)$$

From (5) it follows that

$$F[G^*.t G^*.n] = -e F[G.t G.n] - \frac{7}{2}\mu e(1+e) F[g_n^2]. \quad (6)$$

It is reasonable to assume that the correlations $F[G.t G.n]$ and $F[G^*.t G^*.n]$ are proportional to one another. Following an impact, the correlation $F[G^*.t G^*.n]$ is partially restituted by the interior flow as $F[G.t G.n]$. Thus we expect that

$$F[G.t G.n] = \lambda(e') F[G^*.t G^*.n], \quad (7)$$

where $\lambda \leq 1$ is function of the coefficient of restitution e' of interior spheres. Combining (6) and (7), we find

$$\frac{F[G.t G.n]}{F[g_n^2]} = -\frac{7}{2}\mu e \left(\frac{1+e}{e+1/\lambda(e')} \right). \quad (8)$$

The form of $\lambda(e')$ is determined through the simulations. We find to a good approximation

$$\lambda(e') \approx e'/2. \quad (9)$$

As Fig. (3) indicates, the results of the simulations agree well with the flux model of (1), (8) and (9).

Fig. 3. Relative flux of fluctuation energy vs. friction in the "all sliding" limit. The diamonds, circles and triangles are $e=e'=0.9, 0.8$ and 0.7 , respectively. The squares are $e=0.9$ and $e'=0.7$. The solid lines are the corresponding predictions of the new model.

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