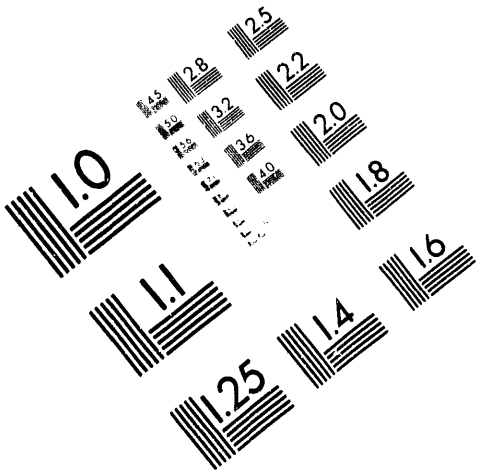

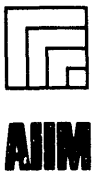

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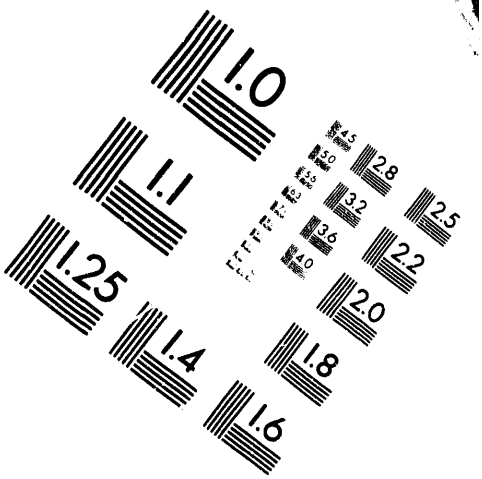

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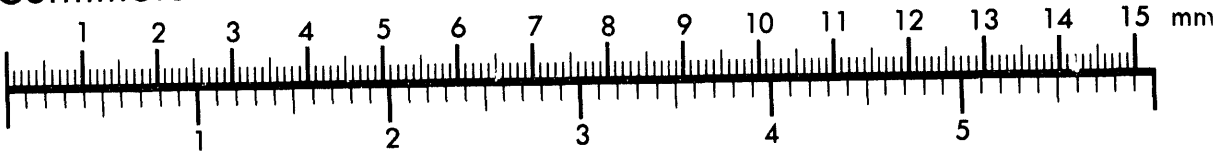

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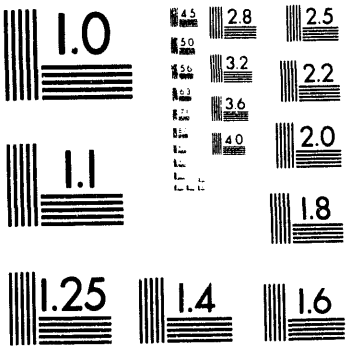

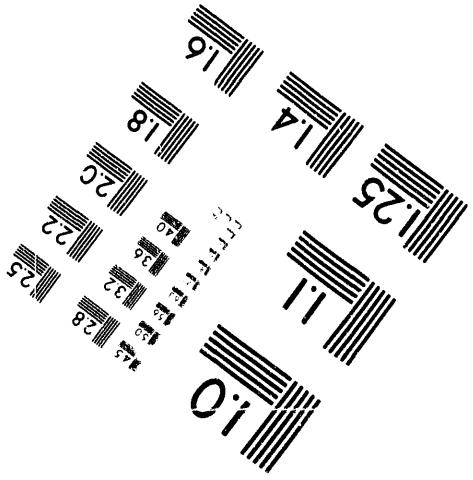

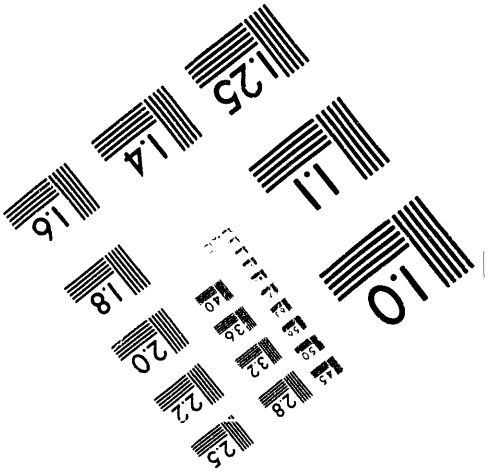

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Dense Inclined Flows: Theory and Experiments

Quarterly Technical Progress Report (January 1, 1993 to March 31, 1993)

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Contract number: DE-AC22-91PC90183
Contract Period of Performance: January 1, 1991 to December 31, 1994
Contractor: Cornell University, Ithaca, NY 14853
Contract Participants: James T. Jenkins, Michel Y. Louge
DOE Project Manager: William C. Peters

US/DOE patent clearance is not required prior to the publication of this document.

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. Its goal is to understand the regime of inclined flow that involves a large, relatively passive mass of granular material moving above a narrow region of intensely sheared, colliding grains. 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 a new series of experiments to measure the collision properties of acetate and glass particles involved in binary collisions or impacting on a flat surface. Results for 3mm glass beads and 6mm acetate spheres are presented here.

In addition, we have finalized the design of a new sensor to measure simultaneously the particle volume fraction near the wall and the normal force of impact from individual collisions.

Finally, we have completed our numerical simulations of the rapid granular flows of spheres interacting with a flat, frictional wall.

During the present reporting period, J. Jenkins has worked with the Scripps Institute.

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1. Collision properties

The previous reports have discussed the collision model and the data reduction. Table 1 summarizes the results that were obtained for glass and acetate spheres. Because the material of the glass spheres is similar to that of the 3mm Jaygo beads used in the Cornell and Florida chutes, we recommend using these values to compare the predictions of the theory and the results of the chute experiments.

Table 1. Sphere properties

Material		Soda lime glass	Cellulose acetate
Finish		polished, grade "200"	ashed
Diameter (mm)		3.18 ± 0.03	5.99 ± 0.03
Density (g/cc)		2.5	1.319
Poisson's ratio		0.22	0.28
Young's modulus (N/m^2)		$7.1\ 10^{10}$	$3.2\ 10^{9}$
binary collisions	e	0.97 ± 0.01	0.89 ± 0.01
	μ	0.084 ± 0.007	0.28 ± 0.02
	β_0	0.47 ± 0.10	0.45 ± 0.06
wall collisions (aluminum plate)	e	0.80 ± 0.01	0.893 ± 0.004
	μ	0.11 ± 0.01	0.19 ± 0.01
	β_0	0.28 ± 0.08	0.47 ± 0.04
Manufacturer		Winsted Precision Ball Co.	Engineering Laboratories
Aluminum Plate		Density = 2.6 g/cc Young's modulus = 7.10^{10} N/m^2 Poisson's ratio = 0.33	

We will soon submit a paper to *Phys. Fluids A* to report these findings.

2. Collision sensor

In the present reporting period, we have finalized the design of the sensor that measures simultaneously the particle volume fraction near the bottom wall of the chute and the impulse exerted by individual particle impacts on its surface. The volume fraction is recorded by a capacitance probe. The center of the probe is fitted with a Kistler load cell that records impulses arising from velocities as small as 0.2 mm/sec for 3mm glass particles. Fig. 1 shows an assembly drawing of the capacitance probe, and Fig. 2 is a cut through its plane of symmetry that shows the location of the load cell.

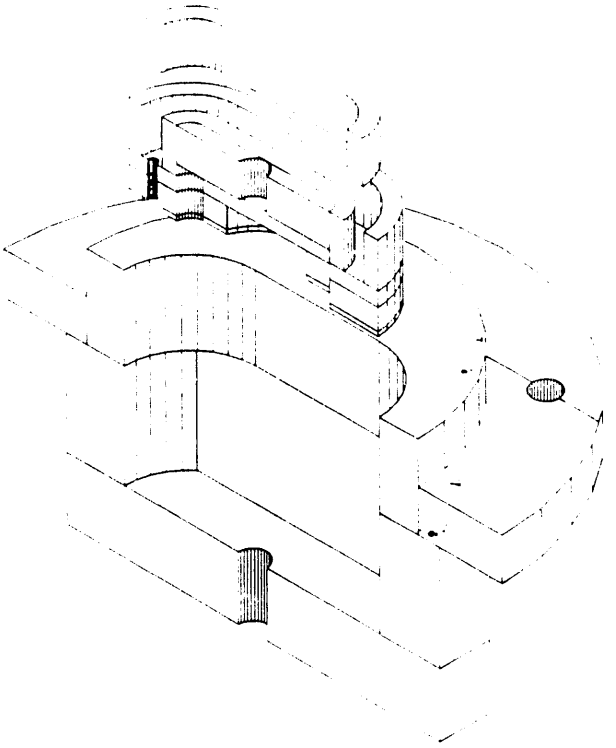

Fig. 1. Assembly drawing of the capacitance probe. This is a cut through the plane of symmetry of the probe. The top piece is the sensor surface of the probe. Its length is 1.54". The intermediate piece is the guard surface. The bottom piece is designed to mount the probe flush with the bottom surface of the chute.

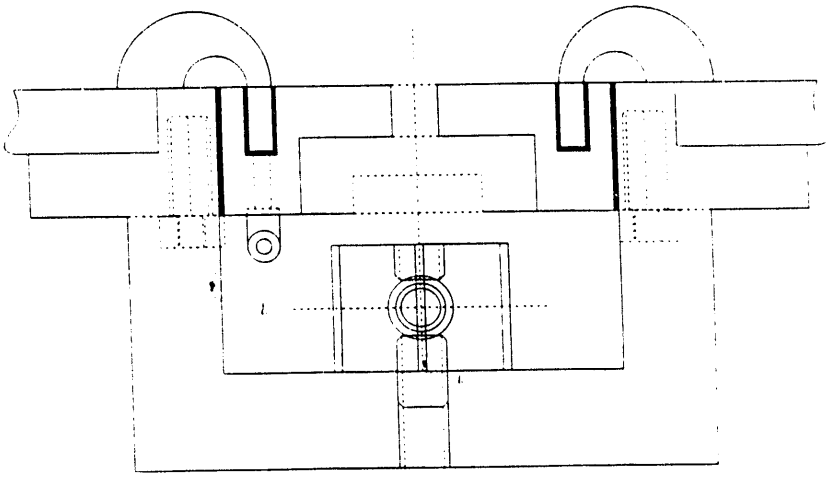

Fig. 2. Section through the long axis of the probe. The load cell is shown without the stud that transmits forces from the particle impacts.

3. Simulations

During the present reporting period, we have completed our simulations of the interaction between a flat, frictional wall and rapid granular flows of frictional spheres. We have written a paper that will soon be submitted to *Phys. Fluids A*. The abstract of this paper follows. Advance copies will be made available at the upcoming GFARO meeting in Newark, NJ.

> We employ computer simulations to test the theory of Jenkins [*J. Applied Mech.* **59**, 120-127 (1992)] for the interaction between a rapid granular flow of spheres and a flat, frictional wall. We examine the boundary conditions that relate the shear stress and energy flux at the wall to the normal stress, slip velocity, and fluctuation energy, and to the parameters that characterize a collision. We find that, while the theory captures the trends of the boundary conditions at low friction, it does not anticipate their behavior at large friction. A critical evaluation of Jenkins' assumptions suggests where his theory may be improved.

For the benefit of the participants in the GFARO, we have run a series of simulations with collision properties consistent with the glass beads of Table 1. The results for the dynamic friction and the normalized flux of fluctuation energy are shown in Figs. 3 and 4.

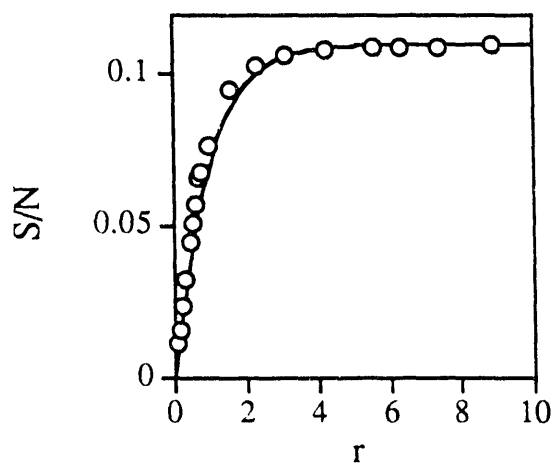

Fig. 3. Dynamic friction coefficient S/N *vs* normalized slip at the contact point $r \equiv g_0/\sqrt{3T}$ for the glass beads of Table 1. The solid line is the empirical fit quoted in the previous quarterly report. The dimensions of the cell are $L_x/\sigma=L_y/\sigma=L_z/\sigma=6$.

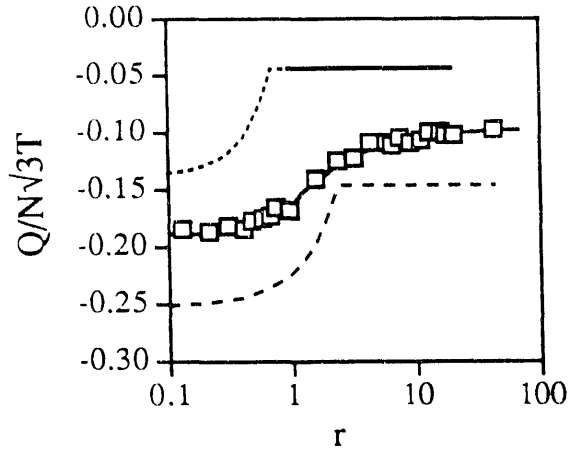

Fig. 4. Normalized flux of fluctuation energy at the contact point $g_0/\sqrt{3T}$. The solid line is a visual fit through the data. The dashed line is the empirical fit given in the previous quarterly report. The heavy line is Jenkins' theory, and the dotted line is an extrapolation of the theory to values of r less than one.

Note that, for the glass beads used in the chute, the flat surface is always dissipating the fluctuation energy of the beads.

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