Dense Inclined Flows: Theory and Experiments*Quarterly Technical Progress Report (April 1, 1995 to June 30, 1995)***Contract number:** DE-AC22-91PC90183**Contract Period of Performance:** January 1, 1991 to December 31, 1996**Contractor:** Cornell University, Ithaca, NY 14853**Contract Participants:** James T. Jenkins, Michel Y. Louge**DOE Project Manager:** Sean PlasynskiUS/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. 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.

1) Experiments

In the present reporting period, we have begun a series of measurements in the chute facility with a bumpy boundary constructed using random two-dimensional packings of 1mm glass spheres. At the inclination of 19° and at several gate openings, we have measured mass flow rate and mass holdup, as well as granular temperature and collision frequency at the bottom wall of the chute. By recording simultaneously the collisional normal stress at the bottom wall and the mass holdup above it, the experiments revealed that, unlike the flat boundary, only a small fraction of the weight of particles is supported by direct impact.

RECEIVED
USDOE/PETC
95 JUL 26 PM 12:47
ACQUISITION & ASSISTANCE DIV.

Fig. 1. Changes in the tangential and normal components of the relative velocity at the contact point for Vitamin-E pills.

We have also completed measurements of the impact properties for several binary collisions of nearly spherical particles used in this and other projects. The Table below summarizes the data obtained. In addition, we have tested vitamin-E pills employed in the rotating drum experiment at Lovelace. Perhaps because these pills are far from rigid

spheres, the resulting collision data could not be interpreted using Walton's three-parameter model. Instead, the pills follow the model of Lun and Savage i.e.,

$$\mathbf{g}' \cdot \mathbf{t} = -\beta \mathbf{g} \cdot \mathbf{t} \quad (1)$$

in the tangential direction and

$$\mathbf{g}' \cdot \mathbf{n} = -e \mathbf{g} \cdot \mathbf{n}, \quad (2)$$

where $\mathbf{g}$ is the relative velocity at contact, $\mathbf{n}$ and $\mathbf{t}$ are the normal and tangential unit vectors, and primes denote conditions after impact. In the experiments shown in Fig.1, we find $\beta = -0.66 \pm 0.37$ and $e = 0.89 \pm 0.07$. We are presently constructing a model of the mechanics of the fluid inside the pill to interpret these measurements.

In the next reporting period, we plan to complete the measurements with the 1mm random bumpy boundary.

2) Theory

During the past quarter, we have continued to improve boundary conditions previously derived for a flat, frictional wall and for a bumpy, frictionless boundary.

Numerical simulation indicated that the derived expression for the energy flux at a flat, frictional wall was deficient in two respects: in the sliding limit, a correlation between the normal and tangential components of the contact velocity that had been ignored was found to be important; and, in the sticking limit, the assumption that all collisions involved stick led to over-predictions of the energy flux. The repair of the expression for the energy flux in these limits has been outlined in previous reports.

In the past quarter, we developed a scaling to link the two limits. This scaling can be the basis of a single, simple analytical expression for the energy flux over the entire range of mean sliding velocity. Calculation of the energy and momentum exchanged in sticking and sliding collisions indicated the expected dependence of the flux of fluctuation energy upon the ratio r of the slip velocity to the r.m.s. value of the velocity fluctuations, and the normalized friction coefficient μ_0 , given for a homogeneous sphere in terms of the coefficient of sliding friction μ , the coefficient of normal restitution e , and the coefficient of tangential restitution β_0 , by $\mu_0 = 7(1+e)\mu / 2(1+\beta_0)$. As r^2 varies between μ_0^2 and $1+\mu_0^2$, these should appear in the combination $\mu_0^2 [-1 + (1+\mu_0^2)/r^2]$. The numerical simulations are presently being interrogated in order to determine an appropriate function of this combination of variables.

Boundary conditions at a bumpy, frictionless boundary were originally derived based on the assumption that the ratio of the slip velocity to the r.m.s. value of the

fluctuation velocity was small. For realistic boundaries, this is not necessarily true. In the past quarter, we have calculated the supply of tangential momentum and the supply of fluctuation energy generated at a bumpy boundary without making this assumption. An illustration of the results is provided below.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.