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Meeting on Flows of Granular Materials in Complex Geometries

edited by

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and
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under the auspices of the Executive Committee
of the International Energy Agency
Implementing Agreement on Fossil Fuel Multiphase Flow Sciences

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Clifton A. Shook, Canada
Arne Ronold, Norway
Rosalind E. Evans, U.K.

This is a report of the Meeting on Flows of Granular Materials in Complex Geometries. It was sponsored by the Pittsburgh Energy Technology Center and Sandia National Laboratories for the International Energy Agency. It was held in Albuquerque, New Mexico, USA, on August 15–16, 1994.

The editors express appreciation to Josephine Roybal and Pam Trent for assistance in the preparation of the manuscript. Especial thanks are due to Sean Plasynski for a major role in the scientific organization of the meeting.

DISCLAIMER

DISCLAIMER

This report is dedicated to the memory of William C. Peters.

Summary

The International Energy Agency Fossil Fuel Multiphase Flow Sciences Agreement has been in effect since 1986. The traditional mechanism for the effort has been information exchange, effected by the inclusion of scientists in annual Executive Committee meetings, by exchange of reports and papers, and by visits of scientists to one another's institutions. In a sequence of informal meetings and at the 1993 Executive Committee meeting, held in Pittsburgh, U.S. in March 1994, it was decided that more intensive interactions could be productive. A candidate for such interactions would be specific projects. Each of these would be initiated through a meeting of scientists in which feasibility of the particular project was decided, followed by relatively intense international co-operation in which the work would be done. This is a report of the first of these meetings.

Official or unofficial representatives from Canada, Italy, Japan, Mexico, the United Kingdom, and the United States met in Albuquerque, New Mexico, U.S., to consider the subject "Flows of Granular Materials in Complex Geometries". Representatives of several other countries expressed interest but were unable to attend this meeting. Sixteen lectures were given on aspects of this topic. It was decided that a co-operative effort was desirable and possible. The most likely candidate for the area of study would be flows in bins and hoppers. Each of the countries wishing to co-operate will pursue funding for its effort. Initial co-ordination will be carried out by the Chairman of the Executive Committee. Exact mechanisms for joint work, information exchange, and reporting will be determined as the project takes form.

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Meeting on Flows of Granular Materials in Complex Geometries
August 15--16, 1994

SUNDAY, AUGUST 14, 1994

5:00 p.m.	Reception and Registration at the Albuquerque Marriott
6:30 p.m.	Dinner on your own

MONDAY, AUGUST 15, 1994

	Chair: Cliff Shook, Canada (Morning) **William C. Peters, U.S. (Afternoon)**
8:00 a.m.	Reception and Refreshments
8:15 a.m.	Introduction - Dan E. Arvizu, SNL/NM William.C. Peters, PETC
8:30 a.m.	Rosalind Evans, Energy Technology Support Unit
9:00 a.m.	Jennifer Sinclair, Carnegie-Mellon University
9:30 a.m.	Clayton Crowe, Washington State University
10:00 a.m.	Break
10:15 a.m.	Raffaella Ocone, University of Naples
10:45 a.m.	Ugur Tüzün, University of Surrey
11:15 a.m.	Peter Schmid, University of Washington
11:45 a.m.	Isaac Goldhirsch, Cambridge Hydrodynamics
12:15 p.m.	Lunch
1:45 p.m.	Keith Walters, University of Nottingham
2:15 p.m.	Guy Metcalfe, Northwestern University
2:45 p.m.	James Salter, Shell Development Company
3:15 p.m.	Break
3:30 p.m..	Baltasar Mena, University, Mexico City
4:00 p.m.	Michael Rotter, University of Edinburgh
4:30 p.m.	Hayley Shen, Clarkson University
5:00 p.m.	Discussion

TUESDAY, AUGUST 16, 1994

	Chair: Masami Nakagawa, Japan (Morning) **Rosalind Evans, U.K. and** **Stephen Passman, U.S. (Afternoon)**
8:00 a.m.	Coffee
8:30 a.m.	John Peace, British Steel
9:00 a.m.	Melany Hunt, California Institute of Technology
9:30 a.m.	Otis Walton, Lawrence Livermore National Laboratory
10:00 a.m.	Break
10:15 a.m.	Charles Campbell, University of Southern California
10:45 a.m.	Eiichi Fukushima, Lovelace Institutes
11:15 a.m.	Masami Nakagawa, Lovelace Institutes
11:45 a.m.	Phil Hsieh, Alcoa
12:15 p.m.	Lunch & videotapes of particle flows
1:15 p.m.	Tour of Lovelace Institutes Laboratories
1:45 p.m.	Discussion
3:00 p.m.	Meeting ends

Particulate Flow Studies by Nuclear Magnetic Resonance

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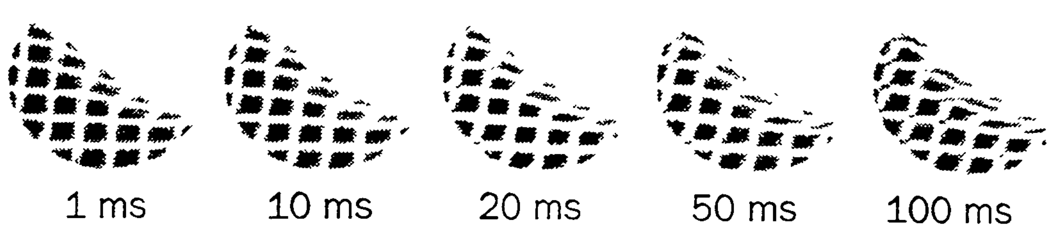
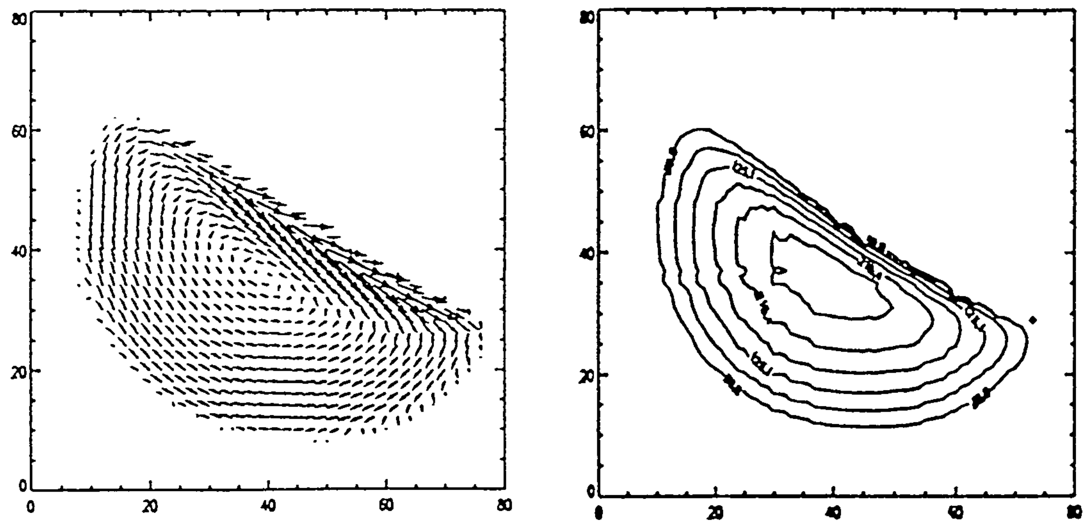
One of the major reasons for the dearth of experimental data for particulate, *i.e.*, granular, flows is the difficulty of non-invasively measuring the distribution of flow parameters in the flow. Nuclear magnetic resonance imaging (NMRI) offers a means of studying several parameters in the flow, far from the walls. We describe measurements of concentration, velocity, and diffusion coefficient distributions of mustard seeds in a partially filled, horizontal acrylic cylinder. NMRI signals are obtained most easily for nuclear spins in liquids. Thus, in order to study the motions of solid particles by NMRI, we use solid particles containing liquid cores. Much of the results described in this note was obtained with mustard seeds containing a liquid (oil) center. They are, on average, spherical with diameter 1.4 mm. These NMRI experiments were performed for steady state flows and required times many orders of magnitude greater than collision times. [We have been working on NMR techniques to make images in tens of milliseconds, however.] The typical acrylic cylinder we used is 3"(76mm) diameter, $\frac{1}{8}$"(3.2mm) wall thickness, and 20" (510mm) long. It is half-filled with the particles and rotated on plastic rollers by an axial shaft connected to a motor located 6' (1830mm) away to reduce the magnetic field intensity at the motor. The angular velocity can be measured by counting the revolutions and it agrees with that measured by NMR. The acrylic and the seeds have sufficient friction for the seeds to not slip against the cylinder. Even if there were slippage, the velocity can be monitored by NMR. We only consider rotation speeds slow enough that the inertial effects are small, *i.e.*, the particles are not close to being airborne and the free surface is nearly straight. For our cylinders, this means rotation speeds less than 30 rpm for which the tangential velocity is 11cm/s and initial horizontal and vertical velocities at the top of the free flowing surface are 6 and 10 cm/s, respectively. There are two methods for measuring velocities. The first is a tagging experiment in which, for example, a grid pattern is non-invasively imbedded into the flowing material and an image made after a suitable delay. The evolution of the grid pattern with time can be displayed in a sequence for flow visualization and quantitative velocity and concentration data can be obtained on the spatial scale of the grid size. This is a simple but robust method that uses an unmodified imaging sequence after the time delay. The figure below shows the evolution of rectilinear grids on mustard seeds flowing in a half-filled cylinder rotating at 18 rpm during the delays indicated. [From M. Nakagawa, *et al.*, Experiments in Fluids 16, 54 (1993).]



The second method is the phase method wherein the phase of the nuclear spin-magnetization is made to correlate with the velocity of the spin in a regulated magnetic field gradient. [A description of this method can be found, for example, in A. Caprihan and E. Fukushima, Physics Reports 198, 195-235 (1990).] Thus, a two-dimensional or even three-D images of velocities and concentration can be obtained by NMR. The trade-off for such complete data sets is the time and computer memory requirements. We have made comparisons between NMR-phase and laser-Doppler measurements for primary and secondary flows in a curved duct and they compare very well. The accompanying figures show a vector velocity (left) and streamline (right) plots for a flow of mustard seeds similar to the above.



In this way, we have obtained full velocity and concentration profiles inside the flowing seeds so that we are able to calculate flux, shear, etc. far away from the walls. In addition, we have begun to study the distribution and anisotropy of particulate diffusion coefficient which is a measure of the spread of particles from an average position during the flow. Finally, it is also possible to study the flow and segregation of multicomponent particulate flow, as it will be described in the presentation by M. Nakagawa.

Computer Simulation of Hopper Flows

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Hoppers are a particularly difficult class of granular flow. From one point of view, they are slow flows and may not be modeled using recently developed rapid granular flow theories. In the past, there were unsuccessful attempts to apply plasticity models to study these flows by assuming that the material was always at incipient yield. However, beyond the problems of continuum modeling, hoppers are converging flows and thus must force the constituent particles to continually reconfigure themselves as the outlet is approached and may invoke the non-continuum nature of the medium.

These were studied with large scale two-dimensional simulations using approximately 20,000 discs within a hopper/bin configuration. Hoppers of various angles were used attached to bins which were 110 particle diameters wide. The hopper outlet had a width of approximately 10 particle diameters. (These dimensions were chosen to correspond, relative to the particle diameter, to those of the experiments of Blair-Fish & Bransby (1973).) The simulation is based on a soft-particle model (see the review by Campbell (1986)). Particles were recirculated by pouring the particles that exit the outlet directly into the top of the bin. Typically the simulations are run for several complete recirculations of the particles through the hopper, a process which may take several weeks on workstation class computers. The statistics gathered include the velocity, concentration, and internal stress fields. Both monodispersed and polydispersed materials were used. Initially, the particles are placed somewhat randomly into hopper/bin with the outlet closed and then gravity is turned on to force the material to settle. This produces a relatively loosely packed granular material. After the hopper is opened, the concentration does not change significantly for polydispersed particles. However, monodispersed particles will generally configure themselves into a hexagonal close pack by the time the particles have completely recirculated once through the hopper.

In many ways, this project was instigated by the x-ray investigations of the flow field in two-dimensional mass-flow hoppers that were performed by Blair-Fish & Bransby (1973) and by Lee, Cowin & Templeton (1974). Those studies showed unsteadiness in the flow field, in which the flow would first move down one side of the hopper and then down the other in a roughly periodic manner. No explanation was given for this behavior. As a computer simulation has access to all of the information about a flow, it is natural vehicle to investigate this phenomenon. The initial simulations performed on monodispersed materials showed a very similar unsteadiness. Lines of particles are colored so that they might be followed. This produces a similar picture of the flow field as the x-ray images obtained by Blair-Fish & Bransby (1973) and Lee, Cowin & Templeton (1974) in which lines of x-ray opaque particles permitted the flow field to be visualized. To assure that the unsteadiness was not a product of the initiation of flow, the simulation was run until all the particles had passed through the hopper once before the particles are colored. However, if a polydispersed sample were used, the unsteadiness disappeared.

The results indicate that the source of the unsteadiness is the alteration in the packing of the particles required as the particle mass physically accommodates its shape, as close as possible, to the converging throat of the hopper. This is particularly difficult as the particles in the bin arrange them into a hexagonal close packed and thus have little room for movement. However, if the particles are not of uniform size, the packing is much more flexible. It is quite possible that the observations of Blair-Fish & Bransby (1973) and Lee, Cowin & Templeton (1974) are solely due to the use of nearly monodispersed materials and are thus absent in most flows of industrial interest.

The simulations have also investigated the stress state internal to the material. A quick observation indicates the inapplicability of plasticity models to hopper flow problems. In particular, plasticity theory supposes that the material is always at imminent yield and thus, the internal ratio of shear stress to pressure should be a constant. The simulations show that the stress ratio varies widely. For monodispersed systems, the stress ratio can greatly exceed the friction coefficient of the material, but the first indications are that the particles surface friction provides the upper limit in polydispersed systems. Of particular interest is the behavior near the corners of the hopper, (where the principle stresses rotate) and near the mouth of the hopper. The stresses near the hopper mouth are somewhat surprising in that the stresses in the radial direction go to zero as would be expected, but the azimuthal stresses are non-zero; i.e. there are still stresses on the hopper walls next to the hopper mouth.

Since plasticity models are apparently inapplicable, the only remaining analytical technique is rapid granular flow theory. As hoppers are noticeably slow flows, it appears on the surface that rapid flow models are inapplicable. This impressions are made somewhat quantitative by examining the ratio of the elastic potential energy of the interparticle contacts and the kinetic energy of the random particle motions. (This ratio should be infinite for a static bed and zero for a true rapid flow.) As expected, this shows that anything approaching rapid flow is only apparent very near the hopper exit.

Collectively, these observations show that hopper flows occur in a regime for which no analytical model has been developed. It is a regime that depends on the strength of nearly static packings and on the non-continuum nature of granular materials. Oddly enough as they are free of unsteadiness, polydispersed systems seem to be easier to handle than monodispersed. Consequently, it will be a long time before a granular systems as complex as hoppers will be well understood.

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REFERENCES

Blair-Fish, P.M., and Bransby, P. L., 1973 Flow patterns and walls stresses in a mass-flow bunker, J. Eng. for Ind. 95, 17–26

Campbell, C. S., 1986, Computer simulation of rapid granular flows, Proc. 10th US National Congress of Applied Mechanics, Austin, Texas, June 1986, ASME, New York, 327–338

Lee, J.; Cowin S. C.; and Templeton, J.S., 1974, An experimental study of the kinematics of flow through hoppers, Trans. Soc. Rheology, 18:2, 247–269

Gas-Particle Flow Phenomena Associated with Pneumatic Transport

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The gas-particle flow in pneumatic transport is complex because of the unsteady and inhomogeneous nature of the flow. The inhomogeneous regions associated with the dense phase transport leads to regions of high shear and steep gradients.

There are two approaches to treating the dynamics of the particulate phase. One approach is to treat the particle field as a fluid and use the equations of motion for a continuum with modified transport properties. An equation for the oscillatory energy, called temperature, is introduced as an auxiliary equation and expressions for pressure and viscosity based on the local temperature are utilized. The other approach is to model the motion of the individual particles and treat the particle-particle interaction as a spring-damper system. Both approaches provide the local void fraction (ϵ) and velocity (U_i).

The equation of continuity for the gas phase is straight forward.

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon V_i). \tag{1}$$

The momentum equation is

$$\frac{\partial}{\partial t}(\rho\epsilon V_i) + \frac{\partial}{\partial x_j}(\rho\epsilon V_i V_j) = -\frac{\partial p}{\partial x_i} - f_i + \frac{\partial}{\partial x_j}\left[\epsilon\mu_t\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right)\right], \tag{2}$$

where f_i is the force on the particles in the i-direction. The force term is currently modeled in the form

$$f_i = \beta(V_i - U_i), \tag{3}$$

where β is a function of the relative speed and void fraction. However, the correlations used for β are based on one dimensional, steady flows.

The following concerns arise:

1. Are the correlations used for sufficiently accurate for three dimensional unsteady flows which occur at the interfaces between the dense and dilute regions of flow?
2. The presence of particles generate a Reynolds stress in the fluid.

$$\tau_{ij} = -\epsilon\rho\overline{\delta V_i \delta V_j}. \tag{4}$$

Is this Reynolds stress adequately modeled by the Boussinesq approximation?

3. How are the correlations affected by particle size distribution?

In fast fluidized beds where the gas-particle flows are more dilute, particle segregation can occur due to the tendency of particles to concentrate in regions of high shear. This is a selective process in which particles with Stokes numbers near unity move toward the peripheries of the large scale vortex structures.

There is also a need to develop a viable flow metering system which provides an in-situ measure of the flow rate of each phase.

Microstructures and Microstatistics in Granular Flows

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Abstract. The inelasticity of the collisions in fluidized granular systems is at the heart of a large number of unusual rheological properties of these systems, the most notable of which are perhaps the observed normal stress differences and multistability. Recently, it has been realized that granular fluids possess highly nontrivial microstructural properties, which have major ramifications on the macroscopic properties of such systems. In particular it has been shown by the author and collaborators that rapid granular fluids are unstable to the formation of dense clusters and that the latter play a major role in determining the stresses in such systems. Another, related phenomenon, (discovered by McNamara and Young) is coined inelastic collapse and, unlike the clustering phenomenon, which is of hydrodynamic nature, it is a microscopic effect. All these effects and others have been verified and studied by using up-to-date molecular-dynamics simulation methods (in one, two and three dimensions). In addition, preliminary kinetic and hydrodynamic equations, describing the dynamics of rapid granular flows, have been developed and some of their properties (in particular linear and nonlinear stability) have been studied. The results of the analytical studies are in agreement with numerical findings and with available experimental findings.

Introduction. When a granular material is strongly sheared the frictional bonds, which hold the granular matter together, are broken and the material is fluidized. In some cases, such as in chute flows one observes a fluidization of the material that is near the chute floor, the rest of the grains being carried on top of this part by virtue of the pressure developed in it; the upper part of the material is at best only partially fluidized. Many of the properties of the flow of a granular material down a chute are determined by the fully fluidized part. In addition there are numerous other applications of engineering and scientific importance that involve the flow of fully fluidized granular matter, usually called rapid granular flow [1].

The experimental studies of the properties of granular flows are usually limited to macroscopic quantities, such as flow rates and overall stresses. Probing the inner or microscopic properties of such flows, while of undeniable importance, is hampered by severe experimental difficulties, though progress in this direction has been reported. An important method of investigating the microscopic properties of granular matter and relating the results to macroscopic properties is afforded by the method of Molecular Dynamics. The latter was originally developed for microscopic studies of molecular systems. It was later adapted [2] to inelastically colliding particles. The original studies were limited to a few hundred particles mainly because of algorithmic difficulties. In our own studies [3] we have employed a modification of the rather modern event-driven simulation method and succeeded in simulating the dynamics of up to millions of particles. This success would have been unessential had it not been for the fact that some properties (*e.g.* cluster sizes) have minimal dimensions and thus do not show up in systems whose sizes are smaller than a specific scale (to be defined below), that characterizes intercluster separations (hence in systems containing too few particles). The realization that some effects in this field are not scale invariant and cannot be tested in small systems (in contrast with hydrodynamic phenomena) is of major consequences since one of the important implications is that it is unjustified to naively scale up laboratory size results to industrial dimensions.

The similarity of the dynamics of rapid granular flows to that of molecular gases has led to a relatively large number of investigation which are based on the kinetic theory of gases. The aim of most of these investigations was to derive macroscopic equations of motion, parallel to the Navier-Stokes equations of fluid dynamics, and boundary conditions for rapid granular flows. The resulting equations bear a striking similarity to the compressible hydrodynamic equations, the main difference being an additional term in the heat equation representing the energy loss due to the inelasticity of the collisions. This result is not surprising since the ingredients of the derivations of the coarse grained equations are similar to those involved in deriving the Navier-Stokes equations from kinetic theory and the set of hydrodynamics fields (density, velocity and temperature) considered in these theories is the same as in hydrodynamics. Some of the predictions of these theories are in reasonable agreement with experimental findings while others, most notably the prediction of a vanishing normal stress difference, are in violent disagreement with experiment. Richman and Jenkins [4] realized that the vanishing of the normal stress difference predicted by the kinetic-based theories followed from an assumption that was copied from the kinetic theory of gases, namely that the single particle distribution function is approximately (to lowest order in perturbation theory) Gaussian. By employing an ansatz, first used by astrophysicists, *i.e.* taking the single particle distribution function to be a generalized Gaussian (*i.e.* proportional to

$$e^{-\frac{1}{2}vKv},$$

where K is a matrix and v is the fluctuating velocity *i.e.* the actual particle velocity minus the local macroscopic velocity), they were able to obtain a nonvanishing normal stress difference. Our numerical results demonstrate that the ansatz used by these authors is by itself only a crude approximation (*cf.* Fig. [3] for a comparison). The need to go beyond the standard practices of the kinetic theory of gases in dealing with granular flows leads one to question the justification of employing only the standard hydrodynamic fields as the pertinent macrofields for the problem of interest. Indeed, even in the realm of the Jenkins-Richman theory one is forced to employ an additional macrofield (namely the matrix field K or its inverse that represents the second order velocity fluctuation tensor). In our own work we have shown the necessity to employ such additional fields, a simple example of which is furnished by the case of one dimensional granular flow, mentioned below.

It is by now clear that flowing granular materials are highly inhomogeneous, highly anisotropic and that they possess specific rheological properties peculiar to them alone, in addition to other rheological characteristics. Below, an attempt is made to present some major physical mechanisms which are, at least partly responsible for these properties. Results of massive Molecular Dynamics simulations serve to illustrate these mechanisms.

Physical Considerations: Collapse and Clustering. As mentioned in the Introduction, one of the major features characterizing rapid granular flows is their inhomogeneity. Consider, for instance, a highly idealized system, *i.e.* a gas of inelastically colliding spheres (whose collisions are characterized, say, by a fixed coefficient of normal restitution) in a box with periodic boundary conditions. Let the initial condition be one of uniform density, macroscopic vanishing velocity and uniform granular temperature.

In addition, it is assumed that the system is not externally forced. Such a system promises *a priori* to be rather dull. One naively expects it to remain in a homogeneous state having vanishing macroscopic velocity while the granular temperature decays to zero due to the inelasticity of the collisions. It turns out that this picture is untrue even when the degree of inelasticity is minute. The reason for this is sketched below.

As in any many body system, one expects the above system to experience fluctuations. Consider a spontaneous fluctuation leading to the emergence of a shear wave of very long wavelength with respect to the mean free path. Since momentum is strictly conserved such a wave will decay extremely slowly; in particular its decay rate can be much slower than that of the granular temperature. One thus expects the slowest possible shear wave (which depends on the geometry and size of the box) to be a dominant mode after some time. Incidentally, this also implies that the rate of decay of the kinetic energy must slow down in order to accommodate the existence of the slowly decaying velocity field. This can be achieved by the system if the particles are arranged in such a way that most collisions are of grazing nature. All of these conclusions are corroborated by our numerical experiments in which the ratio of the system size to the mean free path isn't too large. When the latter ratio exceeds a certain number (see below) the dominant shear wave gives way to another, much more dramatic phenomenon, namely to the emergence of dense clusters. The latter phenomenon can be understood on the basis of the following considerations. Once the shear wave is dominant, the system contains regions of relatively high shear rate and other regions in which the shear rate is relatively low. A domain in which the shear rate is relatively high is heated by the effect of viscous heating. As a result the granular temperature and, consequently, the pressure in such a region become elevated. This causes pressure driven motion of the granular fluid from the relatively high pressure regions to the low pressure domain. In a regular fluid (elastic collisions) this situation is clearly reversed by the dynamics of the system. In a granular fluid, once the density is increased in a domain in which the shear rate is low, the rate of inelastic collisions there is increased, leading to a lowering of the kinetic energy per particle in this domain and consequently to a further lowering of the pressure in it. The result is that even more particles are "sucked" into such a domain. Thus once an increase in density is started in a given domain, the process of clustering is self perpetuating, limited only by the processes that tend to disperse mass agglomerations, such as diffusion. It can be shown that the typical distance between clusters created by the just described $\ell/\sqrt{1-e^2}$, where ℓ denotes the mean free path and e is the coefficient of normal restitution. Clearly, when the system size is smaller than the above scale one will not observe clustering but the instability leading to the dominance of a shear wave mode will be observed. These predictions are in agreement with the numerical results.

The physical mechanisms described in the above are clearly relevant to forced systems [5] as well. Some technical details may differ but the governing principles remain the same. In a sheared system, for instance, a linear mechanism gives rise to oblique layers (at about 45° to the streamwise direction) of relatively dense material interspersed among relatively dilute layers. Clusters form in the latter, then they are rotated by the flow; in the process of rotation a strongly nonlinear mechanism, by which clusters collide, leads to the restoration of the originally shaped oblique layers. Figs.[1,2] illustrates this mechanism. It is perhaps worth mentioning that the clustering mechanism is a nonlinear phenomenon, as one may deduce *e.g.* from the fact that the viscous heating mechanism is essential in this effect.

Another phenomenon which typifies granular gases is that of inelastic collapse [6]. The basic mechanism at work in this case is the same that responsible for the relaxation, in a finite time, of a ball inelastically bouncing off a floor. This effect was shown to exist in one and two dimensional systems and it may exist in three dimensional systems as well. Its full ramifications are yet to be studied. The collapse phenomenon, in contrast with the clustering phenomenon, is of nonhydrodynamic nature. In the one dimensional case we have shown [7] that collapse is always preceded by clustering. Physically this seems to be of general validity though it has not been proven yet.

Some Theoretical and Numerical Results. In all theories of rapid granular flows, which are based on kinetic considerations, the single and two particle distribution functions, which are necessary for the development of the coarse grained equations, are modeled or assumed rather than derived. We have set out to find the nature of the single particle distribution function on the basis of an analysis of the appropriate Boltzmann equations. Among our major results we wish to mention the following: (1) In one dimensional systems [7] the distribution function is not Gaussian; it assumes a two-hump form with a local minimum at zero velocity. (2). The solution [8] of the Boltzmann equation in three dimensions for an unforced system, assuming isotropy (which may be locally relevant in dilute domains of actual systems) is Gaussian-like for low speeds and exponential for high speeds. The crossover between the two speed domains occurs at a speed which is a universal function of the coefficient of restitution, and which diverges, as it should, in the elastic limit. (3). The single particle distribution for a two dimensional sheared granular system [9] is of the form: $\exp(a(\theta) + b(\theta)v + c(\theta)v^2)$, where v is the norm of the local velocity fluctuation vector, a, b and c are angle dependent coefficients where θ is the angle between the macroscopic and fluctuation velocity vectors.

While much more is to be done in order to elucidate the full nature of the single particle distribution function, it is already clear at this point that the functional form of this entity is very different from what was hitherto assumed and that this difference is of major consequences (*e.g.* in determining the normal stress difference).

Summary. We wish to conclude by reiterating that an understanding of the microstructural properties of granular fluids is of paramount importance not only for a full theoretical understanding of these systems but also for the purpose of constructing reliable engineering models. In this effort the role of massive molecular dynamics simulations as a source of detailed microstructural and global information cannot be overstated.

REFERENCES

1. C.S. Campbell, "Rapid granular flows", Ann, Revs. Fluid Mech., **22** 57–92 (1990) and numerous refs. therein.

2. O.R. Walton and R.L. Braun, Acta Mechanica, **63**, 73–86 (1986), cf. also numerous refs. in (1) above.

3. a. I. Goldhirsch and G. Zanetti, Phys. Rev. Lett., **70**, 1619–1662 (1993).
b. I. Goldhirsch, M.-L. Tan and G. Zanetti, J. Sci. Comp., **8** (1), 1–39 (1993).

4. J.T. Jenkins and M.W. Richman, J. Fluid Mech., **192**, 313–328 (1988).

5. I. Goldhirsch and M.-L. Tan, "Dynamics of clusters in 2D sheared granular flows", preprint (1994).

6. S. McNamara and W.R. Young, Phys. Fluids **A4**, 496–504 (1992).

7. N. Sela and I. Goldhirsch, "Hydrodynamics of a one dimensional granular medium" , preprint (1994).

8. I. Goldhirsch and S.H. Noskowicz, "The solution of the Boltzmann equation for an unforced isotropic granular gas", unpublished.

9. I. Goldhirsch and M.-L. Tan, "The single particle distribution function in a dilute granular shear flow", preprint (1994).

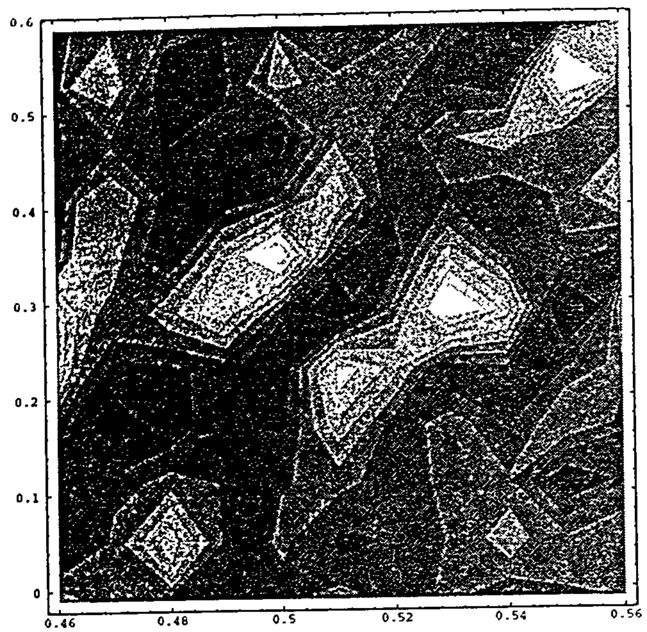

Figure 1: A closed-in view of the density field around two clusters about to interact with each other. The shade code for the contour plot is: lighter greys for higher density and darker for lower densities. The parameters of the sheared system, whose domain lies in the range $0 < x < 1, -0.5 < y < 0.5$ with the x-direction being the streamwise direction, are given by: the coefficient of normal restitution, $\tilde{e} = 0.6$, the total number of particles, $N = 200000$, the solid fraction, $\nu = 0.05$, and the shear rate, $\gamma = 100$.

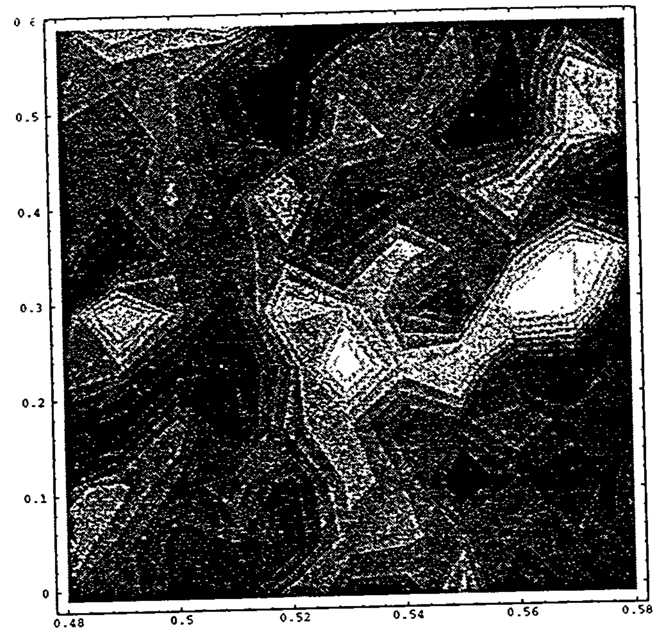

Figure 2: The density field in the same vicinity as the one shown in Fig.1 but at a later time that corresponds to the lapse of 1 collision per particle in the system following the configuration in Fig.1.

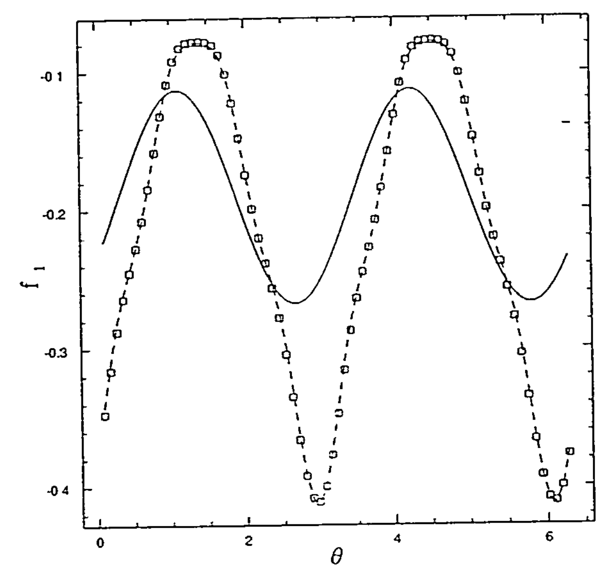

Figure 3: The generalized Gaussian distribution for dilute shear flow, $f_1^{(JR)}$, versus the actual distribution as measured in our simulations and its fit given by the form as mentioned in the text. The □ points correspond to the measured distribution, while the dashed line correspond to the fit and the solid line to $f_1^{(JR)}$. All distributions are shown versus angle θ at fixed velocity $v = 1.6$ and fixed average temperature $T = 0.11$

Experimental Techniques for Granular Material Flows

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Introduction. Over the past decade, researchers have made considerable progress in developing constitutive relations for granular materials using dense-gas kinetic theory and using computer simulations. However, there has been less work on experimental studies of granular material flows, which may be due to the lack of appropriate instrumentation. Most experimental studies that have been performed measure bulk transport effect such as the normal and shear stresses or the average heat transfer coefficient, and do not measure the local flow properties such as the velocities, the solid fraction and the granular temperature.

The purpose of this extended abstract is to outline the experimental techniques for measuring both local and average quantities in flows of granular materials. The emphasis is on the experimental work that has taken place at Caltech.

Local Measurements. Measurements of the local velocity, the solid fraction and the granular temperature are crucial to understanding the transport processes of granular material flows. A technique based on the back scattering from two closely-spaced fiber optic probes was used by Ahn, Brennen & Sabersky (1991) and Hsiau & Hunt (1993) to measure the average and fluctuating components of the velocity in the flow direction, and to measure a one-dimensional solid fraction. The two fiber optic probes are placed on the outside of the transparent test-section walls and are aligned in the direction of the flow with about two particle diameters between the probes. The passage of a particle is recorded by both probes and the signals are cross-correlated to determine the delay time between signals. The local stream-wise velocity is determined from the spacing between the probes and the time delay. By averaging over 100-200 particles, the ensemble-average velocity, $< u >$, and the ensemble-average of the square of the stream-wise velocity fluctuations, $< u'^2 >$, can be determined. In addition, the number of particle passages per unit time detected by the probe was divided by the mean velocity to obtain the characteristic particle spacing, C_{1D}, and a one-dimensional solid fraction was calculated from the ratio of the particle diameter to the characteristic spacing, $\nu_{1D} = C_{1D}/d$. The uncertainty in the average velocity measurements is approximately 3% of the average speed; however, the uncertainty in the velocity fluctuations is significantly larger, and the technique becomes unreliable for flows with a large fluctuating component or for flows with a significant transverse component.

A new technique, developed by Taylor & Hunt (1993) and Natarajan, Hunt & Taylor (1994), measures the transverse component of the velocity. This technique relies on video recordings of brightly-colored tracer particles in a sea of clear particles. The video images are digitized using a frame grabber board and a personal computer. The digitized images are enhanced to increase the contrast of the tracers, and then the digital images are cross-correlated to determine the vertical and the horizontal shift of the particle. Two components of the local velocity, u and v, are then determined from the shift and the time between images. The test section is divided into small bins, and the local average velocity and the square of the velocity fluctuations are defined for each bin by averaging over all particles moving within that bin. Generally, this means an average over 100-200 particles. The uncertainty in this measurement again appears to be within 3% for the average velocities and approximately 10% for the velocity fluctuations. The uncertainty results from the finite number of pixels per particle and the effects of the uneven lighting and coloring of the particles. The local velocity measurements have also been used to determine the local diffusion coefficient (Natarajan, Hunt & Taylor, 1994).

Both of these techniques are for two-dimensional flows since the movement of the particles is measured adjacent to a solid surface or at a free surface and not internal to the flow. This limitation is minimized by making the measurements through a polished glass plate. Experimental observations indicate that the velocity of the particles adjacent to the polished glass surface may be about 10% less than the velocity of the particles internal to the flow.

Measurements of Average Transport Processes. Granular flow studies at Caltech have included measurements of wall shear stress, wall heat flux, and bulk diffusive flux. Ahn, Brennen & Sabersky (1991) measured the wall stress for granular flows down an inclined chute. The shear stress gauge consists of a plate supported by strain-gauge flexures that were oriented to measure an applied shear force. A hole was cut into the chute and the surface was replaced by the instrumented plate; a small gap (smaller than the size of a particle) surrounded the plate to allow for a displacement of the plate during shearing.

The heat transfer coefficient for a flow granular materials was measured by placing a small heated surface into a section of the chute base (Spelt, Brennen & Sabersky, 1982; Patton, Sabersky & Brennen, 1986). The heat transfer coefficient was determined from the heat flux to the plate and the difference between the plate temperature and the free stream temperature. These measurements are important, not only in modeling heat transfer in granular material flows, but also as a sensitive indicator to changes in flow structure because the heat transfer is significantly affected by changes in the flow density.

In Hsiau & Hunt (1993), measurements were made of the average diffusive flux of particles in a sheared flow. The experimental configuration was a vertical channel with a feed hopper that contained a splitter plate through the center. Differently-colored but otherwise identical granular material was placed on other side of the splitter plate. Downstream of the splitter plate the differently colored materials began to mix, and the growth of the mixing layer was recorded for different flow conditions.

REFERENCES

Ahn H., Brennen C.E., & Sabersky R.H., 1991, "Measurements of Velocity, Velocity Fluctuation, Density and Stresses in Chute Flows of Granular Materials," J. Appl. Mech., 58, 792–803.

Hsiau, S.S. & Hunt, M.L., 1993, "Shear-Induced Particle Diffusion and Longitudinal Velocity Fluctuations in a Granular-Flow Mixing Layer," J. Fluid Mech., 251, 299–313.

Natarajan, V.V.R., Hunt, M.L. & Taylor, E.D., 1994, "Determination of Particle Trajectories to Study the Diffusive Behavior of Sheared Granular Materials," manuscript in preparation.

Patton, J.S., Sabersky, R.H. & Brennen, C.E., 1986, "Convective Heat Transfer to Rapidly Flowing, Granular Materials," Int. J. Heat Mass Transf., 29, 1263–1269.

Spelt, J.K., Brennen, C.E. & Sabersky, R.H., 1982, "Heat Transfer to Flowing Granular Materials," Int. J. Heat Mass Transf., 25, 791–796.

Taylor, E.D. & Hunt, M.L., 1993, "Measurements of Velocity Fluctuations in a Granular Flow," Powders & Grains 93, ed. C. Thorton, Balkema Publishers, Rotterdam, Netherlands, 275–279.

Rates, Patterns, and Models for Mixing and Segregation of Granular Solids

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Powder mixing plays an important role in a number of industries ranging from pharmaceuticals and food to ceramics and explosives. Given its fundamental technological importance [1,2], surprisingly little is known about the basic kinematics of flowing and mixing granular materials. For instance, no theory can suggest the optimal method or time required to mix medicinal powders to a specified uniformity. To suggest why this is so, consider that from a theoretical viewpoint, mixing problems appear complex and unwieldy, while from an applied viewpoint, it is often expedient to focus on the details of particular cases without ever searching for underlying structure. As a step towards uncovering basic principles, it is clearly desirable to identify granular mixing problems admitting clean and focused experimentation together with a healthy measure of theoretical tractability.

A quasi-two-dimensional disk partially filled with differently colored passive particles and rotating about its axis seems to satisfy these requirements. This geometry could be considered a two-dimensional tube or drum mixer. Because of their industrial use and because they display axial segregation bands, many people have considered three-dimensional tube mixers. To our knowledge only Hogg *et al.* [3] have previously considered transverse mixing in the cross-section of a tube. Here we report the results of experiments and a model based only on geometric considerations. Comparison of mixing patterns from experiment and the simulated model shows excellent agreement. Moreover, we can predict with the model and measure mixing rates and (with differently sized particles) demixing rates as a function of the fill level f in the disk.

Experimentally, the disk is thin enough for the dynamics to occur in a plane and be visually apparent. The particles are dyed table salt, which are cubes with a mean side length of 0.5 mm. When we wish to provoke segregation, the particles are a mixture of salt and sugar balls, which have a size ratio of 1/5. As the cell rotates, the flat material surface rotates until it reaches an angle $\theta_f \approx 60°$, at which point the static equilibrium of the particles fails and an avalanche occurs. After the avalanche the surface returns to its angle of repose $\theta_r \approx 52°$. The rotation speed is slow enough so that avalanche motion ceases completely before the next avalanche begins. Note that the rotation of the disk is steady, but the motion of the surface, which causes mixing, is iterative. This is important to our being able to reduce the dynamics of the mixing to a map. We call the flow quasi-two-dimensional because, even though individual particles may move between the front and back bounding surfaces as the particles avalanche down the surface, we observe through the front and back glass covers that the macroscopic structures—boundaries, streaks, and core—extend entirely through the material layer. While individual grains in the experiment may take a three-dimensional path during an avalanche, large-scale structures remain planar.

The basis of the geometric model is to notice that the angles θ_f and θ_r define a wedge. To the extent that the surface can be considered a straight line, it is the material inside this wedge that the avalanche takes from one side of the container to the other. As a first approximation the motion of grains is modeled as taking the upper surface wedge and flipping it across the center line. The mixing is accomplished by a mathematical map of the wedge into itself. The results to date have used both a random map, i.e. the points in the wedge are rearranged randomly, and a simple deterministic map. Other maps could be devised to more closely probe the mixing dynamics, but the simple random map does a surprisingly good job. The geometric reasoning is not limited to circular domains.

Based only on an examination of the geometry of wedges and their intersections, several predictions can be made. (1) Mixing should be faster for lower fill levels for $f < 1/2$. (2) Mixing should be very slow for $f = 1/2$. (3) A non-mixing core should appear for all $f > 1/2+\epsilon$ whose fractional area grows as f^2 and where ϵ is the size of the surface boundary layer. Each prediction of the model is testable and is found qualitatively in the experiments.

Mixing rates are determined by tracking the positions of the centroids of the colors. The centroid positions are normalized (for both experiment and computation) to that of the whole material so each centroid starts one unit from the overall center of mass. When the material is perfectly mixed, the color centroids coincide with each other at the origin. The centroids' orbits oscillate and decay exponentially. The decay time-constant γ and oscillation period are measured as a function of f. The simulations verify the predictions from geometric reasoning: mixing is fast for lower f and decreases to near zero at $f = 1/2$, though the calculated mixing rates are consistently higher than those measured from the experiment.

As a practical matter we would like to know how efficient a powder mixer a rotating disk might be. The area mixed is $A(f)$, where A is the area of the disk and without loss of generality we may take $A = 1$. The characteristic mixing time (in units of revolutions) is $1/\gamma$. The most efficient operation point is that which maximizes $\gamma A(f)$ the area mixed per time. The maximum efficiency measured efficiency of $0.4A$/revolution occurs around $f = 0.2$.

The mixing flow in the thin drum is asymmetric with in principle a large number of degrees of freedom. It is extraordinary that so simple a model based only on geometry does so well. For the subject of granular solids mixing the quasi-two-dimensional mixer is an excellent system with which to make precise measurements and physically motivated models.

REFERENCES

[1] Fan, L.T., Chen, Y. and Lai, F.S., *Powder Tech.* **61**, 255–287 (1990).

[2] Ennis, B.J, Green, J. and Davies, R. *ChemE. Progress* April, 31–43 (1994).

[3] Hogg, R. and Fuerstenau, D.W., *Powder Tech.* **6**, 139–148 (1972).

Particle Segregation in a Horizontal Rotating Cylinder

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Introduction. Particle segregation has gained much attention from many disciplines of science and engineering communities. Recently, segregation in vibrated granular particles has attracted many researchers in physics community. (See for example, Knight, *et al.*, 1993 and Rosato, *et al.*, 1987) Particle segregation also occurs in many important industrial situations such as chute flow, discharge from hoppers, and rotating kilns.

In this report we focus our attention on segregation phenomena in a kiln or rotating cylinder. Three different modes of segregation phenomena have been known to occur in a horizontal cylinder (Das Gupta, 1991). Among them, radial segregation has been most extensively studied. Less known is a phenomena called axial segregation. This was most likely first observed by Oyama in 1939 but progress in modeling has been hampered largely because of the inability to see motion deep inside a container so as to determine the full, three-dimensional flow patterns.

At The Lovelace Institutes we have been non-invasively studying flows of different particles in a rotating cylinder (Nakagawa, *et al.*, 1993) using NMRI (Nuclear magnetic Resonance Imaging) and more recently started to investigate radial as well as axial segregation by imaging various stages of these processes. We report some preliminary findings of the radial segregation due to density difference and the three-dimensional nature of axial segregation.

Radial Segregation. For this experiment, glass beads and mustard seeds of the same average diameter (1.5mm) were used. This choice of mixture of particles provided radial segregation due to density difference. Each constituent occupied 25% of cylinder volume and the half-filled cylinder containing initially well mixed particles was rotated at 4.8 rpm. NMR images were taken in the middle of the cylinder far from the end caps after 1, 2, 3, 10, and 20 rotations.

Fig. 1 shows the concentration of light particles (mustard seeds) along a line AB going through the center of the cylinder. Even after only one rotation, the bottom region was occupied almost entirely by mustard seeds and remained that way thereafter. The core region was also relatively quick to organize itself as a region whose constituent is mostly heavier particles (glass beads). In the top region, the concentration of mustard seeds was still increasing when the cylinder was stopped after 20 rotations

Axial Segregation. In order to gain some insights about mechanism(s) for merging/splitting of axial bands (Nakagawa, 1994) we have used pharmaceutical pills, which contain vitamin oil, of 1 and 4mm diameters to image both segregating constituents at various stages of the process. These particles are round, hard and considerably less frictional than most of the particles we have used, such as sand particles, glass beads, plastic beads, sesame seeds, poppy seeds, and mustard seeds.

The cylinder was half-filled with the 50-50 mixture. The particles were initially well mixed and rotated at 22 rpm. In less than 2 minutes, there was a well-defined radially segregated core of small particles extending from one end of the cylinder to another. About one hour later, particles were segregated into two obvious bands. These two bands looked like two separate bands of small and large particles if viewed from outside, but the NMRI found that they actually consisted of a band of small particles for about 1/3 of the cylinder length and from that end, there was a core of small particles that extends all the way to far end of the cylinder (Fig. 2a). In 20 minutes the length of the small band grew to the half the cylinder length and the core of small particles inside the band of large particles now disappeared completely (Fig. 2b). This segregation process, including an intermediate process of migration of the core of small particles, has never been observed before. In another set of the same kind of experiment, the positions of bands of large and small particles were interchanged, so the formation of a band on one side of the cylinder was by chance and was not influenced by the end cap or any other external conditions.

REFERENCES

S. Das Guputa, D. V. Khakhar, and S. K. Bhatia, Powder Tech. 67, 145 (1991),

J. B. Knight, H. M. Jager, and S. R. Nagel, Phys. Rev. Lett., 70, 3728 (1993),

M. Nakagawa, S. A. Altobelli, A. Caprihan, E. Fukushima, and E-K Jeong, Experiments in Fluids 16, 54 (1993)

M. Nakagawa, Chem. Engng. Sci. (in press, 1993),

Y. Oyama, Bull. Inst. Phys. Chem. Res. , Rep. 5, 600 (1939),

A. Rosato, K. J. Strandburg, F. Prinz, and R. H. Swendsen, Phys. Rev. Lett. 58, 1038 (1987)

Rheology of Granular Materials

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In this work, we report mostly on the methodology of research on granular flow of our own group, and we give a brief summary of results obtained and on work in progress. We do not in any way claim that our report covers the whole area of research capabilities existing in Italy on the subject. Indeed, there are very active groups of research in Naples and L'Aquila who work on fluidized beds, and some information on the activity of these groups will be given orally if there is time for doing so; there are other groups in both academia and industry, but we are not prepared to give any significant information on the activity of those.

Also, we note that, while the Seminar is held within the scope of the IEA Fossil Fuel Multiphase Flow Sciences Agreement, its title refers to Granular Materials, and we therefore do not touch at all on research in multiphase systems other than particle-fluid ones.

Rheological Approach to Granular Flow: The Pseudo-Thermodynamic Theory. A large fraction of the existing theories of Granular Flow (see *e.g.*, Ocone *et al.* 1993) is aimed at establishing the mechanical behavior of the particulate phase; in this they are clearly rheological theories. A fraction of these theories have to do with dry granular materials (*i.e.*, the results are in principle applicable only in the absence of an interstitial fluid). In practice, theories of dry granular flow may be applicable to situations where, although there is an interstitial fluid, it does not play any major role. However, the existing theories have also been applied to particle-fluid systems, by considering the fluid and the particles as constituting two interpenetrating continua which exert a mutual interaction; even in this extension, the emphasis has been on writing down constitutive equations for the particulate phase (which may, unfrequently, or may not, more commonly, contain parameters characteristic of the interstitial fluid phase).

The methodology on which these theories are based is that of statistical mechanics, and in this sense it does not differ from the methodology typically used in the analysis of the rheology of polymers. However, there are two important differences, both of which make the rheology of granular materials significantly more complex (at the conceptual level) than that of polymeric materials. Most of our recent work has been aimed at addressing ways to take into account these conceptually crucial differences.

First of all, statistical mechanics, as used in the analysis of the rheology of polymers, often makes use of thermodynamic concepts. If one tries to do the same for granular materials, one finds that a thermodynamic theory is not available, since the scale of description of the statistical analysis is (somewhat larger than) that of particles, *i.e.*, it is very significantly larger than that of molecules, even if macromolecules (Astarita and Ocone 1994). It follows that one cannot use classical thermodynamic theory, but some sort of large-scale statistical thermodynamics needs to be considered. Second, and more important, there are problems with the equivalent of the first law, because the fluctuation energy of the particulate phase, U, may be continuously dissipated at a rate I to true thermal energy by the inelasticity of particle-particle collisions. (Contrary to the formally analogous case of gases, a granular material cannot remain in a thermalized state without a continuous supply of mechanical energy, Q, which compensates the rate of dissipation I). Finally, while the concept of "pseudo-temperature", T, of the particulate phase has been available in the literature for a long time, there is of course no space for a pseudo-thermodynamic theory unless one also introduces the concept of pseudo-entropy, a concept which is not available in the classical formulation of granular flow theories.

We have therefore, as a first step in the elucidation of these matters, developed a pseudo-thermodynamic theory of granular flow rheology (Ocone and Astarita 1993). The theory is based on a modification of the Clausius-Duhem inequality (which is needed because of the appearance of the term I in both the first and the second law), following lines of thought presented in detail by Truesdell (1985). The theory is based on the classical formulation of the constitutive equations for the particulate phase, where fluctuating energy and pseudo-temperature are regarded as the same thing. This leads to a theory where granular materials are seen to be materials with entropic elasticity. The value of the pseudo-entropy can actually be calculated from existing constitutive theories, to within its value at a reference state; quantities such as pseudo-enthalpy, Gibbs and Helmholtz free pseudo-energies, and the like, can also be calculated, and the analogs of the classical Maxwell relations can be shown to hold true for them — in spite of the non-classical term I appearing in the basic formulation.

Compressibility of Granular Materials: Density Wave Propagation. When the particulate phase is regarded as a continuum, it is obviously a compressible one: even if (as is usually assumed to be the case) individual particles have a constant density, the local density of the particulate phase may change because the solid volume fraction may change. It follows that one needs to analyze the compressible flow dynamics of the particulate phase, and it is here that the introduction of the concept of pseudo-entropy plays a very important role — theories of compressible flow make crucial use of the concept of entropy.

Our first step (Ocone and Astarita 1994a) has been to analyze the simplest possible problem in compressible flow, the speed of propagation of infinitesimal disturbances of particulate phase density, or the "speed of pseudo-sound". It is interesting that, in the analysis of this problem, the presence of the term I does not play any role, and one obtains again the classical result that the square of the speed of pseudo-sound equals the inverse of the iso-pseudo-entropic compressibility.

The next step (Ocone and Astarita 1994b) was to analyze the speed of propagation of finite discontinuities of particulate phase density; these can be classified as detonations and deflagrations (with detonations corresponding to compression shocks, and deflagrations to rarefaction shocks). The former propagate super-pseudo-sonically, the latter ones sub-pseudo-sonically. Comparison with existing experimental data turns out to show qualitative agreement, although quantitative agreement cannot be claimed at this stage.

In classical compressible flow theory, rarefaction shocks are known to be unstable (infinitesimal waves run away from them), while compression shocks are inherently stable. Available experimental data show that indeed rarefaction shocks are unstable. This is one of the problems we are currently addressing (Astarita *et al.* 1994), but in this case some significant difficulties arise in considering the extension of the classical theory to granular materials.

The problem is obviously an unsteady state one, and one needs to write down the balances of mass, momentum and energy. In the classical case of gases, these three equations constitute a three-dimensional homogeneous hyperbolic problem which can be approached by diagonalizing the resulting vector equation and trying to find the Riemann invariants of it. When doing so, the balance of energy is seen to reduce to the condition that, if the initial density distribution is isoentropic, it will stay isoentropic at all times, and the problem reduces to a two-dimensional one for which the Riemann invariants can easily be found.

In the case of granular flow, the presence of the term $Q-I$ (which in unsteady conditions is not zero) makes the system a non-homogeneous one, and even if one starts from an iso-pseudo-entropic condition, at later times the system will not be iso-pseudo-entropic. Hence the problem remains a three-dimensional one, the Riemann invariants cannot be found, and one is reduced to numerical solution of the relevant equations for some appropriate set of initial conditions, with all the attendant difficulties of both pragmatic and conceptual type.

Granular Materials with Non-Entropic Elasticity. The constitutive theories of granular flow discussed so far are, as was hinted above, based on the identification of fluctuating energy per unit mass, U, with pseudo-temperature T. Apart from this actual identification, the crucial point is that these theories imply that U is a unique function of T (Statement A). Now in any logically consistent thermodynamic theory A implies that stresses are proportional to T, and that in isothermal deformations elastic energy is accumulated via a decrease of entropy — *i.e.*, that the materials have entropic elasticity (or viscoelasticity, as the case may be).

Some recent work by Jenkins and McTigue (1990) considers the case where the interstitial fluid is so viscous that particle-particle interactions are mediated by viscous stresses in the fluid, so that the constitutive equation for the particulate phase includes as a parameter the fluid viscosity, but not the particle intrinsic density. A simple dimensional argument implies that this assumption can only hold true if the reversible pressure (*i.e.*, that part of the isotropic part of the particulate phase stress tensor which only does reversible work) is not proportional to T which, by a reverse implication, means that Jenkins-type granular materials are not materials with entropic elasticity, and therefore not only cannot U be identified with T, U is not even a unique function of T.

We are currently investigating (Ocone and Astarita 1994c) the pseudo-thermodynamic implications of this type of theory. Since U is not a unique function of T, one cannot develop a pseudo-thermodynamic theory unless one decides how U depends not only on T but also on the solid volume fraction. While dimensional (or, more properly, scaling) arguments suggest how to do so, it is not yet clear whether the resulting pseudo-thermodynamic theory makes sense in some asymptotic sense, and, if it does, exactly in what asymptote it is tenable.

REFERENCES

Astarita, G., and R. Ocone, "Large Scale Statistical Thermodynamics and Wave Propagation in Granular Flow", I&EC Research, in press (1994).

Astarita, T., R. Ocone, and G. Astarita, "Thermal Relaxation Behind Pressure Waves in Granular Flow", Accepted for oral presentation at Fluidization VIII, (1994).

Jenkins, J. T., and D. F. McTigue, "Transport Processes in Concentrated Suspensions: The role of Particle Fluctuations", in "Two Phase Flows and Waves", D. D. Joseph and D. G. Schaeffer Eds., Springer-Verlag, New York (1990).

Ocone, R., and G. Astarita, "A Pseudo-Thermodynamic Theory of Granular Flow Rheology", J. of Rheology, 37, 727–742, (1993).

Ocone, R., and G. Astarita, "On Waves of Particulate Phase Pressure in Granular Materials", J. of Rheology, 38, 129–139, (1994a).

Ocone, R., and G. Astarita, "Compression and Rarefaction Waves in Granular Flow", Powder Technology, in press (1994b).

Ocone, R., and G. Astarita, "Grain Inertia and Fluid Viscosity Dominated Granular Flow: A Thermodynamic Analysis", Accepted for presentation at the Society of Rheology Meeting, Philadelphia, October (1994c).

Ocone, R., S. Sundaresan, and R. Jackson, "Gas-Particle Flow in a Duct of Arbitrary Inclination with Particle-Particle Interactions", AIChE Journal, 39, 1261–1271, (1993).

Truesdell, C. A., "Rational Thermodynamics", 2nd Ed., McGraw Hill, New York 1985.

The Development of 12% Chromium Steels for Bulk Solids Handling

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Introduction. British Steel has become one of the most efficient steel manufacturers in the world, with improvements seen in productivity, quality, delivery, performance and response to the needs of the worldwide market place.

Part of this success stems from reductions in engineering down-time in the key areas of its operations, by the introduction of better engineering design and the use of enhanced materials where significant cost benefits have been identified.

The nature of producing iron and steel requires the use and handling of a number of raw materials with wide ranging properties, each calling for a different approach to solving the difficulties encountered in storing and transporting these materials to their respective point of use. Over 30 million tonnes of raw materials were handled in making 14 million tonnes of liquid steel at British Steel's five integrated works during 1988-89.

Typically solid raw materials include, iron ore, coal, limestone, ferro alloys and scrap. Intermediate products such as coke and sinter create their own specific handling and wear problems.

Coals and ores are shipped into the United Kingdom from several sources, and have a great variety of properties. Some coals can be extremely wet and sticky, whereas others are dry and dusty. The ores handled can vary from wet concentrate and fines to heavy angular rubble and pellets. These raw materials are off-loaded, stored and conveyed through British Steel's own port facilities. British Steel also produces the majority of its own coke and all its own sinter. Coke and sinter are frequently handled at elevated temperatures which cause other handling problems.

Lessons learned from this experience in materials handling have been extended to other industries including coal and gold mining, fossil fuel power generation and limestone handling, and holds potential for other metal winning industries.

Bulk Solids Handling. The problems encountered when handling minerals and other bulk solids include wear due to abrasion, erosion/impact and corrosion in varying degrees. Poor flow and the difficulties of handling materials at elevated temperatures are two other major problems experienced.

Wear can never be totally eliminated but can be significantly reduced by the correct choice of lining. Lining choice is dependent mainly upon the physical characteristics of the solids handled, which in the case of steelworks vary in size from large angular lumps of iron ore, coke and sinter, to fine cohesive materials such as lime or coal.

There is a wide range of lining materials on the market, which include glass, rubber, ceramics, ultra-high molecular weight polyethylene (UHMWP), high chromium tiles, bulk welded plate and quenched and tempered low alloy steel plate. Each of these linings has specific properties in meeting impact, temperature, corrosion and flow promotion. However, none has the combination of properties offered by stainless steels.

Abrasive Wear. Two-body abrasive wear is possibly the greatest cause of lining failure and occurs as a result of the sliding action of bulk solids over a contact surface. This type of wear is common within chutes, feeders and mass flow hoppers and silos. Mass flow hoppers and silos in particular suffer excessive wear in high pressure areas, namely the surcharge transition and the diverging sections towards the outlet. Also, mass flow hoppers and silos require a low friction contact surface to prevent material caking on walls and thus causing ratholing and arching problems. The advantages of stainless steel for this duty are that friction angles as low as 15 degrees can be achieved. Glass tiles may offer a lower friction angle between lining and flowing bulk solid, but experiences show that glass abrades very readily and is thus unsuitable for service duties.

Impact or Erosive Wear. Wear due to impact or erosion is predominantly within belt conveyor transfer chutes and to a lesser extent in hoppers and silos. Factors affecting erosion are impact angle between bulk solid and lining, particle velocity, particle angularity and hardness and the properties of the lining on the contact surface. With the exception of rubber, wear due to impact is inversely proportional to contact surface hardness providing the surface does not spall. It is also important to maintain a low friction angle between bulk solid and contact surface in impact areas. Erosion of contact surfaces can lead to increasing frictional values due to gouging and spalling. Ideally, contact surfaces should polish to a low friction value, and retain that value over their service lives, to prevent bulk solid adhesion, build-up and blocking.

Flow of Bulk Solids. Core flow designs of bunkers may benefit from the installation of low friction linings in order to promote flow and make them self-emptying. Even if a bunker is of a good mass flow design, there are still occasions when flow problems such as ratholing occur, and the incidence of such problems can be reduced by the use of low friction linings to reduce the bulk solid/wall (or kinematic) angle of friction. These problems generally occur when either the characteristics of the bulk solid being handled change in some way, *e.g.* an increase in moisture content, or a change in the process might require that a different bulk solid be handled in an existing system.

The friction angles of different lining materials against coal have been determined in the laboratory using a Jenike shear cell. It was found that cold rolled ferritic stainless steels and UHMWP have far lower friction angles than rusted mild steel, rubber and concrete, and approach the friction angle of glass. Although glass has a lower friction angle it is much less impact resistant than either stainless steel or UHMWP. Both of these materials have performed well on British Steel sites when used to overcome the problems of flow in chutes, feeders and bunkers.

In the case of stainless steel, tests have shown that the Jenike friction angle is dependent on surface roughness which in turn is directly related to the coefficient of friction. Using Centre Line Average (CLA) as a measure of surface roughness, laboratory tests have been conducted on different materials, including stainless steel with different surface finishes. The results show that mechanically polished stainless steel such as the No. 4 dull polished finish exhibits directionality with respect to angle of friction. Careful consideration must be given to the orientation of mechanically polished stainless steel when installing it as a lining, so that the polishing direction is aligned with the direction of material flow.

Corrosion. Corrosion, both by water and acids, aggravates wear and is a particularly important factor which can affect the flow properties of a lining. Although corrosive liquors will exacerbate the surface roughening process, the situation is found to be prevalent even in the common conditions of neutral pH. This has been highlighted in tests conducted to assess the effect of dwell time of fine, wet coal on the polished surfaces of carbon and stainless steels for a twenty-four hour period. The friction angle for the mild steel increased significantly after twenty-four hours contact time, while that for the stainless steel remained constant. Superficial pitting of the surface of the carbon steel had occurred, while the stainless steel surface remained unaffected. Corrosion of mild steel is particularly important if, for instance, a wet cohesive material is to be stored inside bunkers where it may remain static for long periods before discharge.

Elevated Temperatures. Bulk materials such as coal, coke and sinter can be handled at elevated temperatures. Ceramic linings such as alumina and basalt are not affected by moderate increases in temperature, but their fixing adhesives are. Generally, alumina and basalt linings should not be used where temperatures exceed 80°C. UHMWP linings soften at temperatures above 100°C, and owing to their relatively high rate of thermal expansion can fail at lower temperatures owing to expansion effects of fixings. Moreover, a major concern with UHMWP linings is fire and smoke risk. In applications where hoppers and chutes are subjected to heat, British Steel specifies the use of stainless steel.

Steel Developments. Stainless steels have been utilised for several years in materials handling applications where corrosion, poor damp flow, or elevated temperature problems exist. The austenitic chromium-nickel stainless steels have been used successfully to alleviate such problems, but a detailed examination of the handling problems of plant engineers has shown that the cost of such materials can be prohibitive and that a combination of mechanical, flow and installation properties may be better achieved through different metallurgical alloys.

Studies of the elemental cost aspects of both the ferritic and martensitic straight chromium steels have shown the greatest potential for mass-market use of sheet and plate lining materials. Their low alloy content provides a low-cost base while fully meeting the corrosion and flow properties required in most bulk solids handling situations.

Moreover, small variations in alloy composition together with processing variations can give rise to a range of steels with ferritic, martensitic and duplex phase balances. These can result in a range of mechanical and fabrication properties and, when correctly selected for the environment and working conditions of service, can yield an optimum blend of flow, impact, fabrication and economic benefits.

Cost Considerations In order to meet the engineers' requirements for low-cost stainless steels which can be produced and used in bulk an initial consideration is raw material costs. Chromium, the chief constituent to provide the flow properties, is a relatively cheap addition, as are manganese and carbon. Nickel, molybdenum and other common alloying elements have far greater cost implications.

Similarly process routes, which are simple and require the minimum of heat treatment and surface finishing stages, have a major impact on through-costs. Consequently, work has been addressed at minimising processing steps which may be necessary for high integrity process vessel installations for example, but may be regarded as a luxury for the solids handling industries. Such an analysis has, for example, shown that a highly abrasion resistant martensitic stainless steel of the 420R type can avoid costly tempering and descaling operations when used for handling rubble ores.

Life-Cycle Benefits. To the initial steel cost must be added the cost of installation which, in turn, is affected by the ease of fixing. A number of techniques specifically designed for the new range of low-cost stainless steel flat products have, as a consequence, been developed.

The costs of wear from impact and abrasion when handling bulk solids materials are an additional and highly relevant feature of the total cost equation, as is the ease of re-installation. In addition to good flow properties, wear must be the minimised and industrial applications have shown the benefit of low life-cycle costs on a range of different carbon, alloy and stainless steels.

Materials Development Program.

Ferritic Composite. Considerable work in the 1970s on 12% chromium steels with titanium stabilisation yielded steels of the HyForm 409 type with a composition balance and works process control aimed squarely at producing a ferritic stainless steel with an optimum blend of formability and weldability in thin section form. These materials can easily be cold formed and welded into such products as chutes and hoppers. As grain growth detracts from weld ductility in thicker sections of 409 type steels the application in solids handling have concentrated on fine solids such as screened or crushed coals where the properties of a cold rolled 2B finish are particularly conducive to good flow.

In order to provide an impact-absorbing medium for use of steels of the 409 type in thicker form a stainless/rubber composite construction has been developed for use with the fine solids handling industries, particularly for handling coal. The use of a cold or hot vulcanised bond between the rubber and stainless sheet has proved an effective measure for low impact conditions while providing ease of assembly, installation and levelling of the working face.

Ferritic Duplex Utility Steels. Ferritic steels of the 409 type can suffer from excessive grain growth and poor ductility of weldments in thicker sections, which has in practice limited sheets to thicknesses around 3 mm. Consequently, the production of a 12% chromium steel with good weld ductility in a variety of thick plate sections for the metallurgical solids handling industries has been identified as a significant target and has been conscientiously approached over this last decade. Stainless steels of the HyFab 3/12 type have resulted with a composition of 11% to 12% chromium, titanium stabilisation, containing low interstitial levels and small amounts of nickel-manganese and silicon.

During processing, this type of steel has a dual phase microstructure consisting of austenite and ferrite. On cooling, the austenite transforms to a martensite containing low interstitial levels. This is then tempered, resulting in a structure of ferrite and tempered martensite which possesses a combination of strength and toughness superior to that of the 409 family of ferritic steels.

The mechanical properties of such a utility grade of stainless steel have been designed to embrace the requirement for good weldability and formability in structural applications and for mildly corrosive environments, where mild and low alloy steels lack the adequate corrosion resistance and where coated products are inappropriate due to the thermal, mechanical or chemical degradation of the coatings. The properties differ from conventional ferritic stainless steels in the critical area of thick-section weldability, and match that of the generally used structural carbon steels. These properties combined with low cost and corrosion resistance in air and water, over ten times better than mild steel, make them highly versatile stainless steels, not only for handling abrasive, damp or high temperature solids, but also for the many associated structural components.

Martensitic, Highly Abrasion-Resistant Steel Plate. In handling ores, coal, limestone and coke, a need to provide a wear-resisting steel combining both high hardness and corrosion resistance for operation in damp conditions has been widely expressed by plant engineers, yet within the constraint of a cost at the bottom of the stainless steel hierarchy. Steel melting technology now permits more tightly controlled analyses, which together with improved control of hot rolled processing has enabled the bulk production of a hard, martensitic stainless steel plate, HyFlow 420R with properties specifically matched to the needs of the heavy minerals handling industries. This steel has been developed to provide a hardness in excess of 400 HV in plate thicknesses ranging from 4 mm to 40 mm, which can be flattened, drilled or stud welded for fixing as liner plates using conventional fabrication equipment.

The ductility of a hard martensitic plate of the 420R type is limited at ambient temperature, although hot forming may be carried out to enable complex shapes to be manufactured.

Further Avenues for Development. A wide range of properties and structures are a consequence of the metallurgical transformations available around the 12% chromium point. Production of consistent properties for these materials has only been possible by tight control in steelmaking and in subsequent hot and cold processing steps.

Further avenues for exploration of the properties of these materials are still being sought and are expected to yield further improvements in process economics, yielding a third generation of low chromium alloys.

Other areas for potential improvements are in weld and HAZ properties of a duplex ferritic product, and on a lower cost processing. Greater austenite stability is a target for improved weldability and different measures can be adopted to achieve this effect.

Factors which have to be considered for even better consistency of weld properties include the Kaltenhauser Factor, the stability of any austenite which forms during solution treatment, and the control of precipitation of carbides/nitrides in order to prevent sensitisation of the steel during welding. The implications on corrosion resistance of any such modifications also have to be considered.

Similarly in examining properties of the martensitic 12% chromium steels the provision of high hardness plate of the 420R type has not prevented the solids handling industry from seeking improvements. Although many successful bulk solids handling applications have been achieved, a need for better cold forming performance has been sought. A hardness trade-off against an improvement of ductility can be achieved by a tempering operation to provide a product with a combination of good hardness of the order of 300 HV with adequate ductility for cold bending operations.

Lining Choice - Case Histories. It is clear that there are a number of products which should be investigated before finally arriving at a decision on the correct material. Issues which should be borne in mind when material selection is being made include:

1. Is a long - or short-term solution required?
   Frequently companies opt for the cheapest solution because they have failed to consider the costs of plant downtime with its associated loss of revenue, or even the additional maintenance engineering effort that is required. There should be some thought given to the life costing which frequently makes the case for a more expensive installation being the more economical over the total life of that lining.

Fixing Systems.

The fixing method depends upon a number of factors which could include:

1. the properties of the material to be used in the lining;
2. the shape of the lining;
3. the frequency of replacement
4. the materials that are to be handled;
5. the costs of installation;
6. the importance of an uninterrupted surface to ensure the best flow conditions; and
7. the environment of the application.

The different methods available for 12% Cr steels are the following:

1. full welding, including seams;
2. drilled and countersunk with:
   - nut and bolts,
   - self-tappers
   - explosively fired pins;
3. stud welding; and
4. chemical bonding.

Installation. To be certain of the very best life and effectiveness of the materials to be used in bunker and chute linings it is vital that there be a very close relationship between the material supplier, the user, the main contractor and the installer if a separate contract be involved.

One of the keys to success is to have an approved and agreed installation system for each material and for each distinct type of application. The approved methods should ideally be established prior to contracts being quoted, and certainly before the contract is placed.

It is just not sufficient to specify the materials to be used in a particular application. The engineers responsible for the operation of the plant should be thoroughly involved in all discussions relating to design, maintenance and installation.

The material supplier should, wherever possible, be made fully aware of the application of the goods he has on offer, and again should have a strong input into the early planning meetings.

Conclusions.

1. As a result of improved controls in steelmaking practice and subsequent processing a second generation range of ferritic, duplex and martensitic products have been developed with varied properties aimed at the specific needs of the minerals and other bulk solids handling industries. These are identified as impact and abrasion resistance, flow promotion and low through life costs.

2. Cost-effective studies and installation techniques have been examined to show the suitability in service life for particular steels of the HyForm 409, HyFab 3/12 and HyFlow 420R types.

3. Studies in improved ductility and consistency of weld properties are being undertaken and may yield a third generation of such steels for the 1990s.

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Flow Observations and Predictions in Full Scale Silos

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This paper presents an outline of recent research completed and of current work in progress on granular solids flow by the Silos Research Group at the University of Edinburgh, Scotland. It relates to issues relevant to the flow of granular solids from storage hoppers, bins and silos, with special relevance to coal. In this work, the term silo is used to refer to all types of container, and the term hopper to the converging section at the bottom of the container. Whilst there are many further relevant studies which the group has undertaken (see References), this paper is confined to recent observations of solids flow and pressures in full scale silos, the prediction of pressures in silos, a new programme of work on comparison of finite element and discrete particle models for granular solids, studies of coal constitutive relations based on triaxial cell measurements and the development of a coal handleability index for coals to be used to predict poor handling in existing industrial plant.

The goals of work on silo and hopper flow. Before beginning an engineering research study, it is important to define the industrial problems which the research is intended to address. In hopper flow, there are three key problems which regularly arise: first, the structural integrity of the hopper may be jeopardized by pressures which are too high or too low; second, the stored solids may hang up in the container; and third, the flow pattern may cause segregation of the solids. All three are related to flow patterns in the silo, but the three phenomena have different characteristics.

High pressures are not in themselves necessarily a serious danger to the silo structure. High pressures must be seen in the context of the structural form and the way in which the structure carries loads. For this reason, local low pressures can be even more damaging than very high symmetrical pressures. This is a complex subject because the silo is a multi-segment shell structure, and is beyond the scope of this paper, but is treated extensively elsewhere [Rotter, 1985, 1990, 1993]. If the silo collapses, the process which it feeds is arrested, and grave economic losses ensue.

Arching over the hopper outlet, ratholing and incomplete cleanout are other means by which the solids flow is arrested. Arching over the outlet is generally attributed to the development of cohesion in the solid, though recent work suggests that the solids dilation requirement, which is often but not always related to the cohesion, must play a role too. Ratholing is the formation of a stable hole down the entire height of a silo, leading to major loss of effective storage capacity, and consequent serious economic losses. Both arching and ratholing are essentially static phenomena, so dynamic analyses are not necessary nor perhaps helpful in addressing these problems.

The third problem is that of segregation caused by flow. This has largely been addressed by the adoption of mass flow silo geometries and careful filling procedures whenever segregation must be avoided. The criteria for mass flow were developed by Jenike and others in the 1960s [Jenike, 1961, 1964] and, whilst some improvements have been made more recently [Drescher, 1992], there does not appear to be great scope for further work on this topic. Funnel flow silos inevitably lead to segregation of the stored solid, so they are only useful for solids where this is not a problem. The flow pattern in a funnel flow silo remains a topic of serious research because asymmetries in the flow pattern can endanger the structural integrity, but the complex form of the pressure distribution, including both low and high pressures, must be defined before useful progress can be made.

The relationship between material properties, filling process, flow patterns, wall pressures, structural stresses and structural failure is a complex one (Fig. 1). The mechanical characteristics of the stored solids and the process by which they are filled into the silo determine the distribution of densities and particle orientations in the silo, which strongly affect the flow pattern [Nielsen, 1983]. The filling process and flow pattern are largely responsible for segregation of the solids. The solids packing and material characteristics also determine whether arching or ratholing will occur across the outlet (Fig. 1). The flow pattern in turn strongly influences the pressures on the silo wall during discharge, so these cannot be predicted with certainty unless the flow pattern itself can be predicted. The pressures on the silo wall are, in general, unsymmetrical and non-uniform. The relationship between these pressures and the stresses which develop in the silo walls depend on shell bending phenomena, which can be very complex, and not easily understood, though they are predictable with finite element analyses. Finally, the silo wall stresses which will induce structural failure are only currently understood for simple cases, and much work remains to be done. These failure strengths can be very dependent on trivially small imperfections in the wall geometry, and the effect of bulk solids stiffness, as well as being difficult to predict even with the best current nonlinear finite element analyses.

In the context of the above discussion, the work described in the following relates to flow and pressures on silo and hopper walls, with the chief goals of investigating structural integrity and reliability of solids flow.

Large full scale tests on grain silos at Karpalund, Sweden, by Nielsen *et al.* A thorough series of full scale tests was performed in the late 1970s and early 1980s on a concrete grain silo at Karpalund in Sweden by the Danish silo research group, led by Nielsen and Askegaard [Hartlen *et al.*, 1984]. The concrete silo (Fig. 2) was 45m high and 7m in diameter, with several different inlet arrangements, and both concentric and eccentric outlets. The silos were very well instrumented, and a major effort over many years was put into interpreting the results. Initial key lessons learned from these tests were that the pressure patterns on silo walls are not symmetrical, that the filling process has a strong effect on the wall pressures, that grains which are long and thin pack to make a very anisotropic bed, which influences both the wall pressures and the flow pattern [Nielsen, 1983], and that imperfections in the silo wall appeared to influence the pressures significantly [Nielsen, 1979]. In addition, a laboratory model was constructed approximately 0.7m in diameter and 4m high, and a centrifuge model about 100mm in diameter and 700mm high. These model tests showed that serious scale effects often occur in silo experiments [Nielsen and Askegaard, 1977; Nielsen and Kristiansen, 1980; Munch-Andersen, 1986; Munch-Andersen and Nielsen, 1986], and much of the focus of later Danish work has been on this issue.

The full data set on the full scale silo was later re-analysed using statistical techniques by Ooi *et al.* [1990, 1991b], revealing that progressive and significant changes occur in the properties of the grain as it is handled, that standard laboratory test procedures do not produce a very good estimate of the grain properties which the silo sees, that the mean axisymmetric pressure component is the same Janssen distribution for both filling and discharge, despite the occurrence of local high pressures at some locations (a higher pressure than Janssen was always balanced by a lower pressure than Janssen elsewhere), and that the unsymmetrical pressures previously seen after filling (Fig. 3) were very repeatable and became exaggerated during discharge. Satisfying reasons for some of the observed phenomena have not yet been found.

Flow pattern observations in full scale silos in Britain. Following many lessons learned from the tests at Karpalund and at the Technical University of Denmark, this project, initiated in 1992, began with the aim of measuring flow patterns in full scale silos, including those in commercial operation. The new tests were to study silos of very different geometry and different materials Most existing experimental observations of flows in silos are based on observations in small scale models, so that they have limited and uncertain relevance to real installations. This project aims to make observations of both flow patterns and the associated wall pressure distributions in full scale silos, and to develop a tool which can be used to measure flow pattern in an operating industrial plant.

Granular solids flows cannot be directly observed at full scale: the silo walls are opaque, the solids are opaque, and the flows are often internal. A review of alternative techniques was undertaken, and the residence times of radio tag markers adopted as the most promising for industrial applications. The first silo on which the system was used was a 200 tonne gypsum silo at British Gypsum [Rotter *et al.*, 1993], which was pneumatically filled and incorporated an inverted cone vibrating discharge aid. When the discharge aid was operating, the flow was found to develop narrow snaking pipe flow patterns up to the top surface. The form of flow pattern was repeatable, but the location of the pipe was not predictable, suggesting that it is very sensitive to small segregations during filling, or to minor movements in the inverted cone which caused the effective opening to vary in size. When the discharge aid was disconnected, the flow became much more uniform, discharging in a traditional funnel flow. These findings were somewhat contrary to expectations.

A considerable effort has been put into developing numerical algorithms to transform residence time observations into flow pattern descriptions. Several different algorithms of increasing complexity have been developed. The results are now displayed as a dynamic computer graphics simulation of the discharge process [Chen *et al.*, 1994]. The relation between wall pressures and flow patterns under conditions of both concentric and eccentric discharge has been investigated in a full scale silo 11m high and 4.2m in diameter. This new silo is heavily instrumented with strain gauges, so that a comprehensive picture of the pressures on the silo walls can be obtained. The results will be used to formulate new design standards for funnel flow silos and for eccentrically discharging silos. This project was strongly supported by the UK Department of Trade and Industry, through the British Materials Handling Board, and by many industrial sponsors (British Steel, British Gypsum, Cerestar, Tarmac Roadstone, Scotneys, Braby, and others). The project is now continuing for a further three years with funding from the Engineering and Physical Sciences Research Council.

Theory for flow channel and pressures under eccentric discharge. Many of the structural failures which occur in silos are attributable to unsymmetrical or eccentric flow. These flows may be caused by deliberate use of an eccentric outlet, or by segregation or other factors leading to asymmetry (Fig. 4). In this study [Rotter, 1986b], a theory was developed to predict the flow channel diameter of a uniform pipe flow eccentric discharge in contact with the silo wall, to deduce the pressures which might be expected to act on the wall, and to provide some guidance on an appropriate criterion of failure for a metal cylindrical structure. This is the first known study to have addressed the problem rigorously and the predictions have been substantially confirmed by more recent experiments on well behaved materials.

Prediction of hopper pressures. The pressures acting on a hopper are needed for the purposes of safe structural design. Three "classical" hopper pressure theories are widely used, those of Walker [1966], Walters [1973] and Jenike *et al.* [1973]. All three are based on simple assumptions [Arnold *et al.*, 1980], both for the stress distributions in the solid and the plastic state of the solid. In the study noted here [Ooi and Rotter, 1989, 1991a], the power of finite element analysis was used to overcome many of the limitations of these simple assumptions, and showed that hopper pressures are very different in kind from cylinder wall pressures: they are chiefly governed by equilibrium considerations. Associated with this study were several investigations of the structural strength of steel silo hoppers under filling and flow pressure regimes [Rotter, 1986a; Teng and Rotter, 1991, 1993]. Although the discharge pressures are invariably much higher than the filling pressures, particularly at the transition, in an axisymmetric steel structure, it is the filling pressure distribution which is most likely to cause failure. This apparent paradox arises from an over-simple view that high pressures must necessarily be bad: this is by no means true in a shell structure.

Finite element and discrete particle models for granular solids. Many researchers throughout the world have attempted to develop computational models to predict granular solids flows and silo wall pressures over the last three decades. Most have adopted a finite element formulation, representing the solid as a continuum with complex elastic-plastic-viscous properties. More recent attempts have been made to use discrete particle modelling to represent solids flow, using a variety of particle interaction laws. Both methods have significant shortcomings, and the two methods are able to address quite different issues successfully.

In this project, extensive international cooperation will be harnessed to investigate the merits of each proposed model in solving a set of standard problems of practical relevance to granular solids flow in silos and silo pressures. The aim is to identify the merits of each technique, and to check a significant number of alternative formulations of each technique on each task to provide some breadth in the assessment. Most of the planned cooperation involves researchers in Britain and Europe, so additional participants are sought. Existing programs based in Edinburgh will be used as the starting point. A further goal is to attempt statistical correlations of predictions from the two methods. The project is funded by the Engineering and Physical Sciences Research Council in the UK.

Coal constitutive relations based on triaxial cell measurements. Continuum models for granular solids in silos generally require a rather complex set of constitutive relations to predict the behaviour successfully. These models require many tests on a given solid to be performed to determine the many parameters which determine the response. The tests are generally conducted in a triaxial cell, which can be used to study a variety of different stress paths, and to make many different dimensional observations of the solid.

Whilst many such triaxial tests have been conducted on "simpler" solids, such as sand, wheat [Ooi and Rotter, 1991b], plastic pellets and powders [Ooi *et al.*, 1993], few tests have been conducted to define the properties of more difficult materials, such as coal. This project has been undertaken in cooperation with Iowa State University, and funded through the Electric Power Research Institute and NATO, to relate measurements made on many coals to the parameters needed for a high quality constitutive law. These tests (Fig. 5) have been used to develop an appropriate parametric description of coal [Ooi and Lohnes, 1994] for application in finite element analyses.

Development of a coal handleability index. The studies of coal are also intended to serve a more practical goal in relation to coal sampling and measurement to assess the handling characteristics when the coal enters the materials handling stream in an existing plant. Existing theories for coal handleability will be extended, and two new test rigs developed for measuring coal properties directly relevant to arching and ratholing. The first of these will be closely based on work undertaken at Iowa State University by Lohnes under EPRI sponsorship [Leverson *et al.*, 1993]. A demonstration of the efficacy of the tests developed there is illustrated in Fig. 6, where the flow rate of some 20 different US coals from a model bin is related to the measured "handleability index". Coals with high indices need large outlet openings, and produced a zero flow rate in the test bin.

The new study will take the work at Iowa forward to make relatively rapid and simple assessments of the performance of a coal in a silo. The parameters involved in the assessment include the density and its variation with particle packing and stress level, the internal friction characteristics, the macroscopic cohesion, wall friction, hopper geometry, stress history, and flow dilation. This project aims to produce a rapid shortcut technique which can distinguish between a coal which will cause arching or ratholing in a silo of known geometry and wall surface, and one which will give trouble-free emptying of the storage.

Summary. A brief overview has been given of a number of major studies undertaken by the Edinburgh Silos Research Group over the last few years. Those chosen relate primarily to solids flow and pressures in silos and hoppers. Other research activities, which are more concerned with silo and hopper structural integrity, may be read from the references.

REFERENCES

1. Arnold, P.C., McLean, A.G. and Roberts, A.W. (1980) "Bulk Solids: Storage, Flow and Handling", Tunra Bulk Solids Handling Research Associates, University of Newcastle, Australia.

2. Drescher, A. (1992) "On the criteria for mass flow in hoppers", Powder Technology, Vol. 73, 251–260.

3. Hartlen, J., Nielsen, J., Ljunggren, L., Martensson, G. and Wigram, S. (1984) "The Wall Pressure in Large Grain Silos", Swedish Council for Building Research, Stockholm, Document D2:1984.

4. Jenike, A.W. (1961), "Gravity Flow of Bulk Solids", Bulletin No. 108, Utah Engineering Experiment Station, Vol. 52, No. 29, October 1961, University of Utah, Salt Lake City, Utah, 309 pages.

5. Jenike, A.W. (1964), "Storage and Flow of Solids", Bulletin No 123 of the Utah Engineering Experiment Station, Vol. 53, No. 26, November 1964, University of Utah, Salt Lake City, Utah, 197 pages.

6. Jenike, A.W., Johanson, J.R. and Carson, J.W. (1973) "Bin Loads - Part 3: Mass Flow Bins", Jnl of Engg for Industry, Trans. ASME, Vol. 95, Series B, No. 1, Feb, 6–12.

7. Leverson, S.M., Lohnes, R.A. and Treiber, B.S. (1993) "An apparatus for the direct measurement of unconfined yield strength of crushed coal", Mining Engineering (to appear).

8. Munch-Andersen, J. (1986) "The Boundary Layer in Rough Silos", Proc. Second Int. Conf. on Bulk Matls Storage Handliing and Transptn, Instn Engrs Aust., Wollongong, July, 160–163.

9. Munch-Andersen, J. and Nielsen, J. (1986) "Size Effects in Large Grain Silos", Bulk Solids Handling, Vol. 6, 885–889.

10. Nielsen, J. (1979) "Opmaling af Silo i Karpalund" (in Danish), Nordic Group for Silo Research, Report No. 4, Technical University of Denmark, Dept. of Structural Engg., 21 pages.

11. Nielsen, J. (1983a) "Load Distribution in Silos Influenced by Anisotropic Grain Behaviour", Proc., Int. Conf. on Bulk Materials Storage, Handling and Transptn, I.E.Aust., Newcastle, August, 226–30.

12. Nielsen, J. and Askegaard, V. (1977) "Scale Errors in Model Tests on Granular Media with special reference to Silo Models" Powder Technology, Vol. 1, No. 1.

13. Nielsen, J. and Kristiansen, N.O. (1980). Related Measurements of Pressure Conditions in Full Scale Barley Silo and in Model Silo. Proc., Int. Conf. on Design of Silos for Strength and Flow, Univ. of Lancaster, Sep.

14. Ooi, J.Y. and Rotter, J.M. (1989) "Elastic and Plastic Predictions of the Storing Pressures in Conical Hoppers", Transactions of Mechanical Engineering, Institution of Engineers, Australia, Vol. ME14, No.3, 165–169.

15. Ooi, J.Y., Rotter, J.M. and Pham, L. (1990) "Systematic and Random Features of Measured Pressures on Full-Scale Silo Walls", Engineering Structures, Vol. 12, No. 2, April, 74–87.

16. Ooi, J.Y. and Rotter, J.M. (1991a) "Elastic Predictions of Pressures in Conical Silo Hoppers", Engineering Structures, Vol. 13, No. 1, Jan., 2–12.

17. Ooi, J.Y. and Rotter, J.M. (1991b) "The Mechanical Behaviour of Wheat under Storage Stress Histories", Proc., International Conference: Bulk Materials - Towards the Year 2000, Institution of Mechanical Engineers, October 29–31, London, 181–186.

18. Ooi, J.Y. and Rotter, J.M. (1991b) "Measured Pressures in Full Scale Silos: A New Understanding", Proc., International Conference: Bulk Materials - Towards the Year 2000, Institution of Mechanical Engineers, October 29–31, London, 195–200.

19. Ooi, J.Y., Soh, W.C., Zhong, Z. and Rotter, J.M. (1993) "Bulk Mechanical Properties of some Dry Granular Solids", Proc., International Symposium: Reliable Flow of Particulate Solids II, EFChE Publication Series No 96, Oslo, 23–24 August, 75–86.

20. Ooi, J.Y. and Lohnes, R.A. (1994) "Constitutive equations for crushed coal", to be submitted to Powder Technology

21. Rotter, J.M. (1985) (ed) Design of Steel Bins for the Storage of Bulk Solids, University of Sydney, Sydney, Australia, 250 pages.

22. Rotter, J.M. (1986a) "On the Significance of Switch Pressures at the Transition in Elevated Steel Bins", Proc., Second International Conference on Bulk Materials Storage Handling and Transportation, Institution of Engineers, Australia, Wollongong, July, 82–88.

23. Rotter, J.M. (1986b) "The Analysis of Steel Bins Subject to Eccentric Discharge", Proc., Second International Conference on Bulk Materials Storage Handling and Transportation, Institution of Engineers, Australia, Wollongong, July, 264–271.

24. Rotter, J.M. (1990) "Structural Design of Light Gauge Silo Hoppers", Journal of Structural Engineering, ASCE, Vol 116, No. 7, July, 1907–1922.

25. Teng, J.G. and Rotter, J.M. (1991) "The Strength of Welded Steel Silo Hoppers under Filling and Flow Pressures", Journal of Structural Engineering, ASCE, Vol. 117, No. 9, 2567–2583.

26. Teng, J.G. and Rotter, J.M. (1993) "Structural Consequences of Filling and Flow Pressures in Steel Hoppers", Transactions of Mechanical Engineering, Special Edition on Bulk Materials Handling, Institution of Engineers, Australia, Vol. ME18, No.1, March, 75–89.

27. Rotter, J.M. (1993) "The Design of Circular Metal Silos for Strength", Proc., International Symposium: Reliable Flow of Particulate Solids II, EFChE Publication Series No 96, Oslo, 23–24 August, 217–234.

28. Rotter, J.M., Ooi, J.Y., Lauder, C., Coker, I., Chen, J.F., and Dale, B.G. (1993) "A Study of the Flow Patterns in an Industrial Silo", Proc., International Symposium: Reliable Flow of Particulate Solids II, EFChE Publication Series No 96, Oslo, 23–24 August, 517–524.

29. Chen, J.F., Ooi, J.Y., Rotter, J.M., Coker, I., Lauder, C., Zhang, K.F. and Dale, B.G. (1994) "Flow Pattern Measurements in a Full Scale Silo", Proc., Advances in Engineering Measurements, British Society for Strain Measurement International Conference, Edinburgh, August.

30. Walker, D.M. (1966) "An Approximate Theory for Pressure and Arching in Hoppers", Chemical Engineering Science, Vol. 21, 975–997.

31. Walters, J.K. (1973) "A Theoretical Analysis of Stresses in Axially-Symmetric Hoppers and Bunkers", Chemical Engineering Science, Vol. 28, No. 3, March, 779–89.

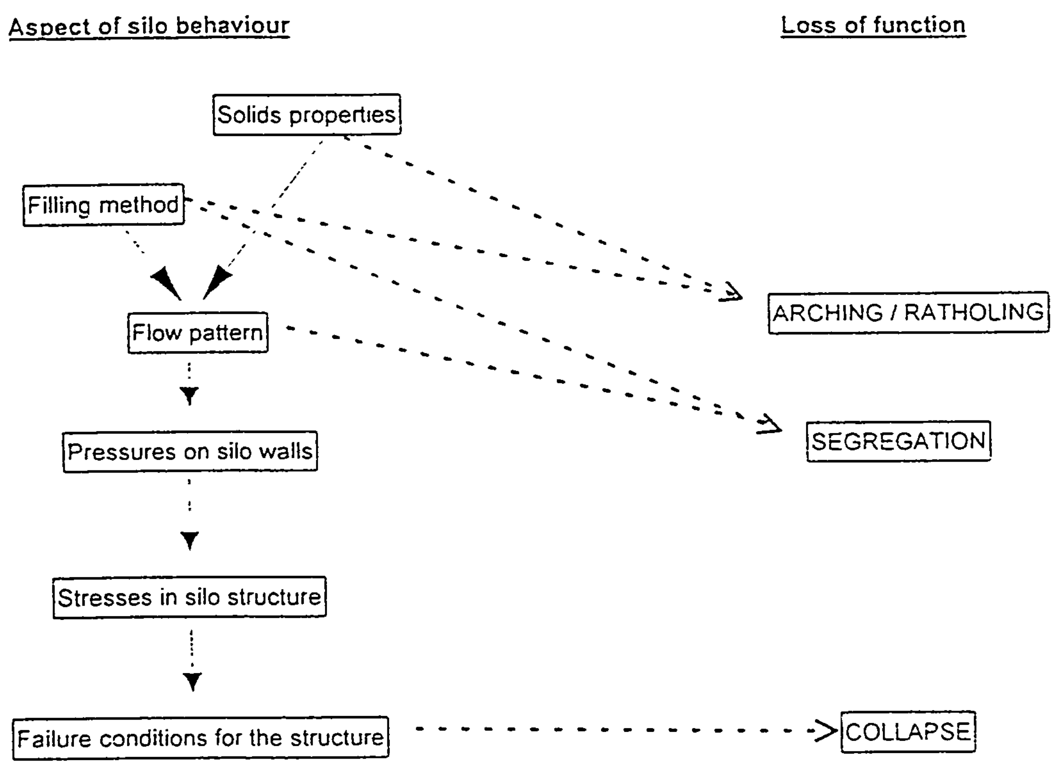


Figure 1. Industrial problems in silos for particulate solids

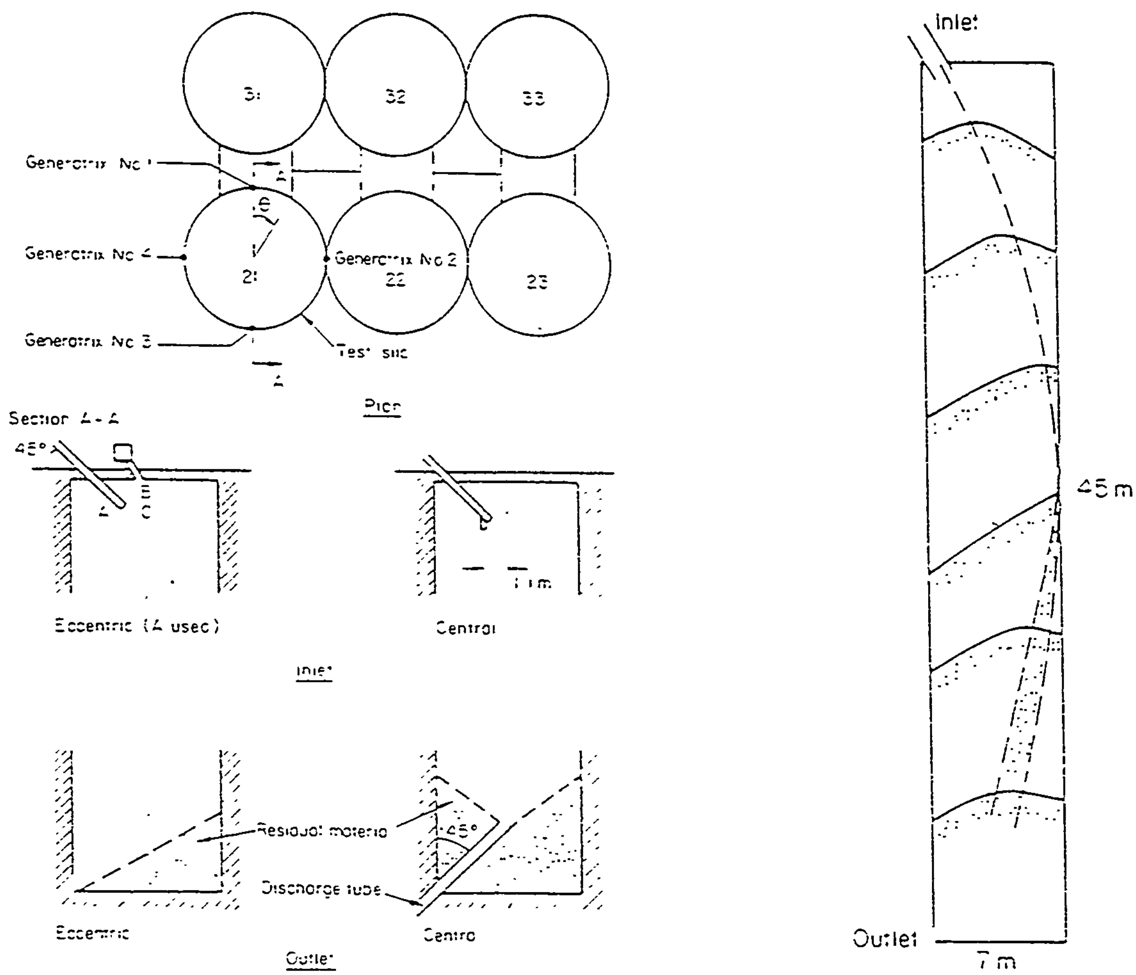
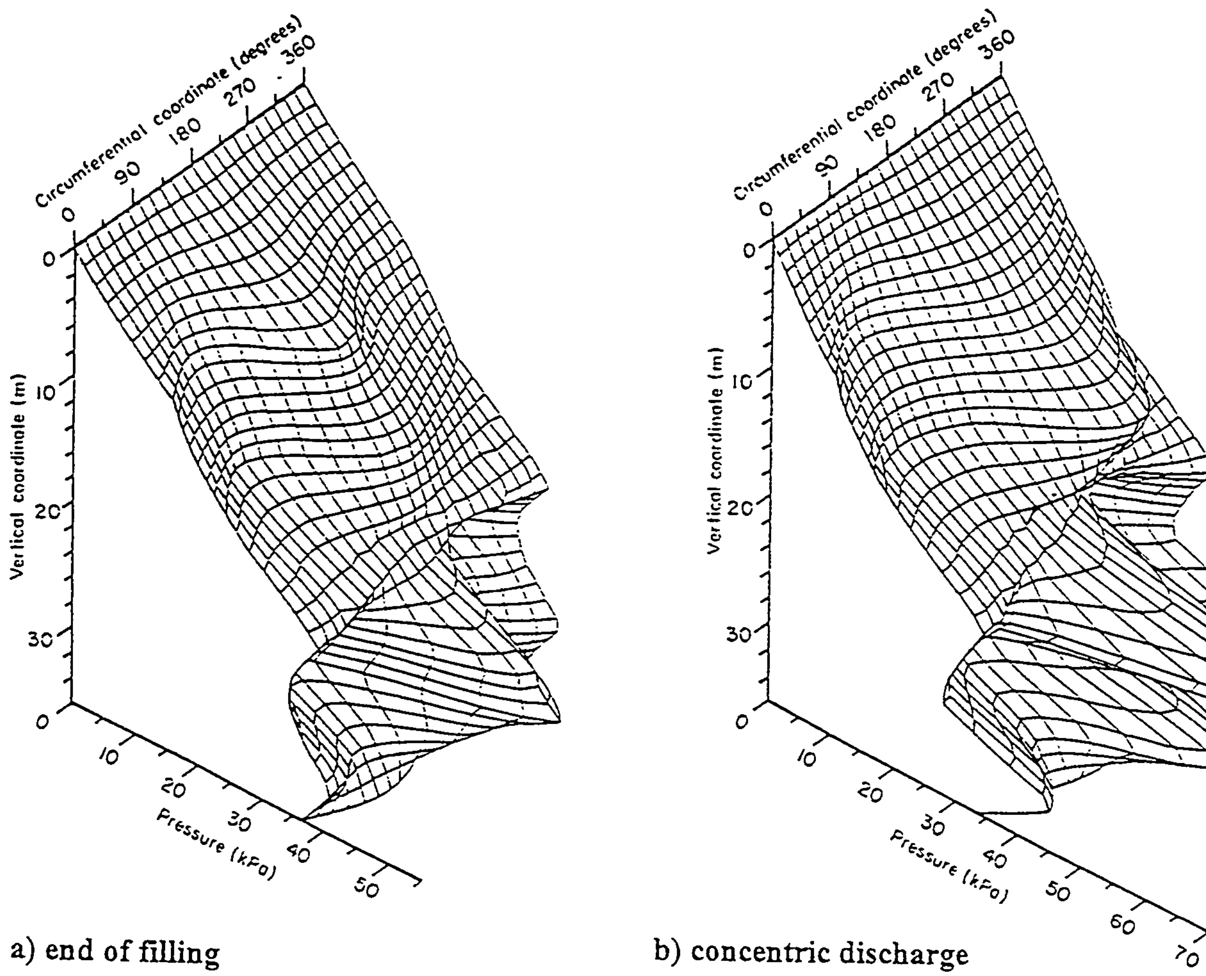


Figure 2. Karpalund silo: geometry and filling patterns



a) end of filling

b) concentric discharge

Figure 3. Unsymmetrical pressures after filling and during discharge

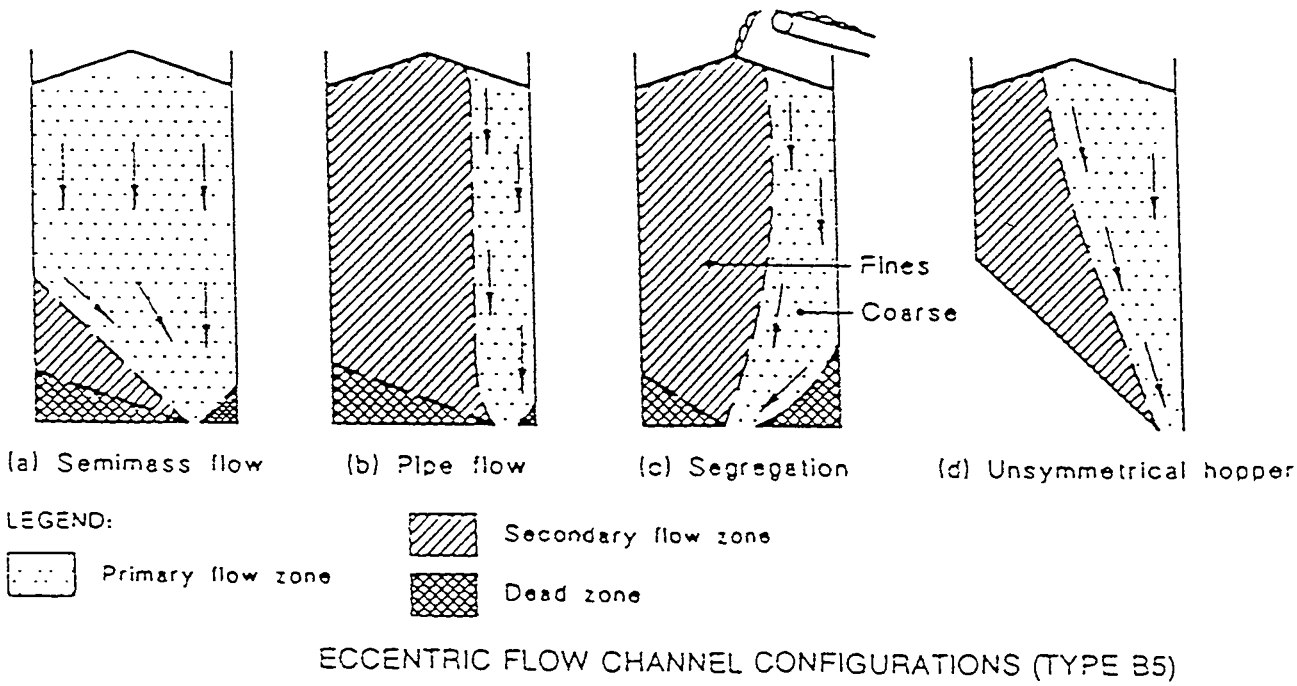


Figure 4. Causes of eccentric flow

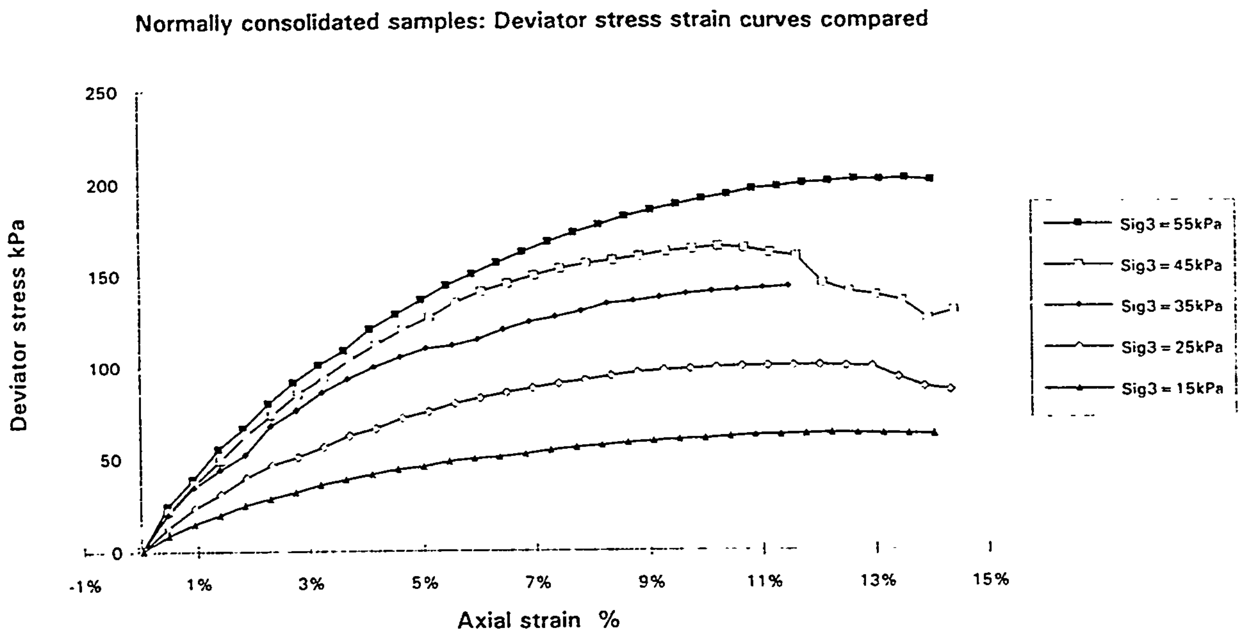


Figure 5. Triaxial test results on Iowa coal blend

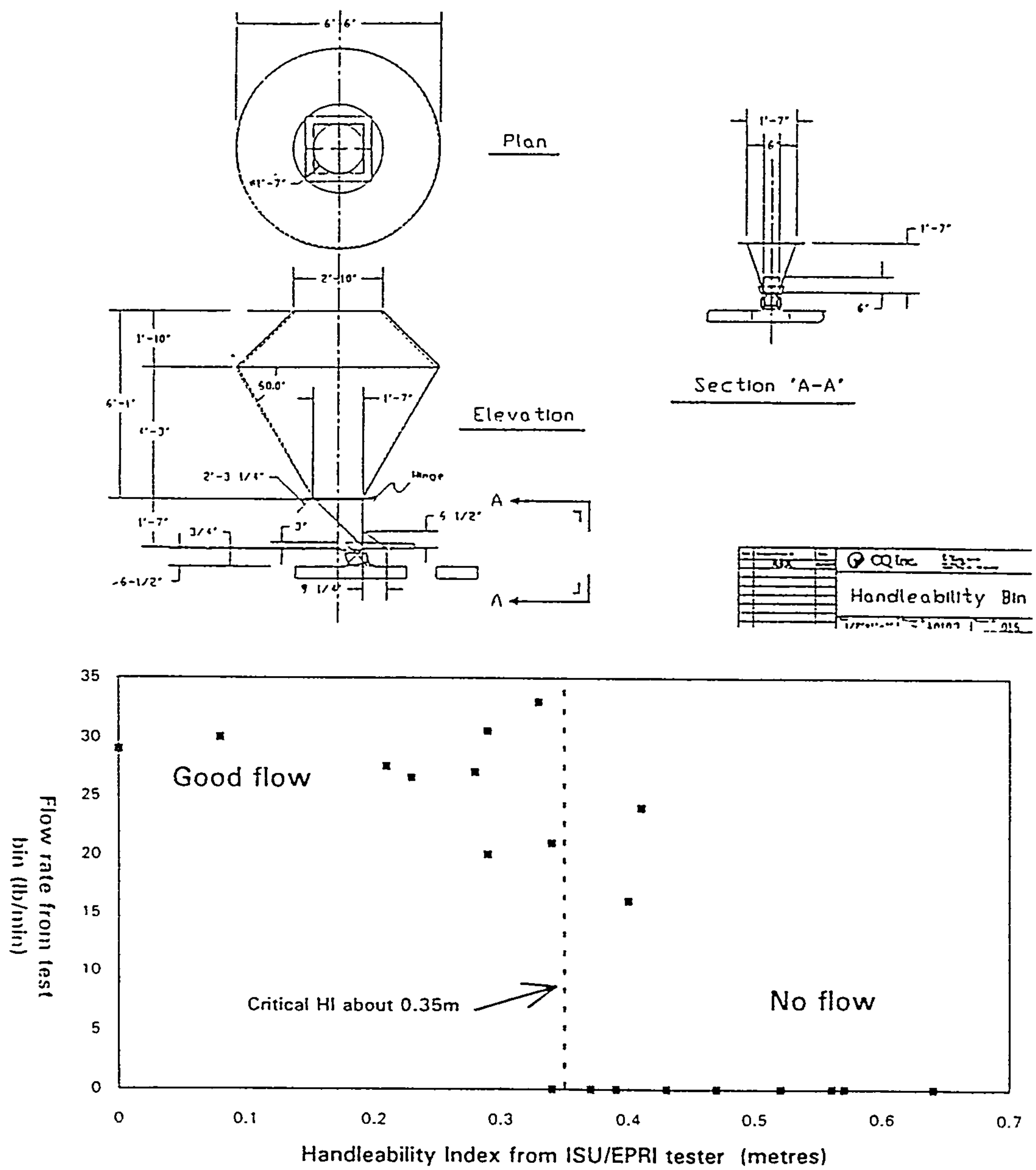


Figure 6. Iowa handleability tests on coal: test hopper and index correlation (after Levorsen *et al.*, 1993)

Formation and Control of Microstructure in Rapid Granular Shear Flows

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Our understanding of many important industrial and geological processes that involve particulate media, such as material processing, sediment transport or coal combustion, are limited by flow maldistributions. Many investigations, both experimental and theoretical, have addressed the constitutive characteristics of rapid granular media and models based on the kinetic theory of gases have been the most successful in duplicating observed behavior.

Only recently have the continuum equations of motion based on these models been used to investigate the stability of particulate flows with respect to infinitesimal wavelike perturbations. Stability equations for infinitesimal three-dimensional disturbances in an unbounded shear flow have been derived using the concept of time dependent wave numbers to represent the interaction of the disturbances with the mean shear. Many investigations are concerned with the temporal stability in the asymptotic limit of large times, but do not allow conclusions about the short-time behavior. Recent investigations, however, touch upon the full stability problem, and give arguments for the possibility of transient growth based on the Orr-mechanism put forward by Orr in the description of the stability of incompressible Newtonian fluid flow. The short- and long-time stability characteristic of rapid granular shear flow is presented here. Rather than concentrating on the eigenvalues of the stability operator, one has to use the Euclidean norm of the solution operator for the description of the stability behavior. Significant transient growth can be observed on a time-scale of the inverse strain rate although the disturbances may be asymptotically stable for large times. This is qualitatively consistent with the measured transient microstructure formation time scale of dense suspensions. This transient growth mechanism is based on the non-orthogonal structure of the eigenvectors of the governing evolution operator and is conjectured to play a dominant role in the stability of granular shear flows. In the context of granular materials, transient growth could lead to finite-amplitude effects, and the transient amplification of solid fraction perturbations might lead to particle clustering observed in experimental and numerical studies.

Once the stability behavior of the governing equations is sufficiently understood it appears quite natural to investigate means to actively manipulate, delay or even suppress the onset of instabilities, even if they only occur transiently. Many possibilities arise to accomplish this, one of them being an imposed volume force that acts on the entire flow field.

A physical realization of this would be the driving of the fluid system by an electrical or magnetic field for charged or magnetic particles, respectively.

In order to successfully control the stability behavior of a system, it is imperative to probe the response behavior of the linear system to an arbitrary outside forcing. To speak in the language of control theory, the transfer function of the linear system is desired. In a second step, this knowledge can then be used to determine time-dependent forcing functions to achieve a certain prescribed output.

While most studies of instabilities in particulate flows were concerned with the evolution of infinitesimal disturbances in granular media governed by the linear evolution operator, the present work extends these investigations to the response of the linear system to a time-dependent global forcing and probes the susceptibility of the solutions to external driving. This problem is known as the linear receptivity problem. Significant receptivity potential has been found for time-steady as well as low-frequency forcing, and low-wavenumber disturbances have been observed to be most receptive to external body forces.

The understanding of the receptivity and response behavior of a system is the first essential step towards controlling and suppressing an unfavorable development of disturbances and is thus of primary interest in a variety of technological processes involving particulate flows. The design of forcing functions poses an inverse problem where the input function is sought, given a desired output behavior. First numerical simulations have shown that by carefully designing external control forces, the formation of clusters by the linear transient mechanism can effectively be weakened or suppressed. The successful manipulation of instabilities in granular materials would give a new perspective to technological applications in that it could considerably enhance the range of parameters under which a process involving granular materials could be operated and, therefore, open new parameter regimes that otherwise would have been prohibited due to instabilities.

Although the above studies of microstructure formation and control have been limited to the case of unbounded uniform shear flow, the mathematical framework easily generalizes to more complex geometries, and it is believed that the physical mechanisms involved in the generation of solid fraction inhomogeneities are also present in geometries encountered in industrial applications. Further studies in this direction are under way. It is therefore of great benefit to enhance our basic understanding of the mechanisms involved in the formation and control of microstructures in rapid granular shear flows.

The Editors wish to express their thanks to Jeana Pineau for her help with this manuscript.

On the Modeling of Granular Flows

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Granular materials encountered in industrial applications often consist of a mixture of sizes, shapes, and material properties. To exactly determine the flow behavior of such mixture requires discrete numerical simulation. However, tracking each individual particle by direct numerical simulation in a complicated flow demands much higher computer power than is currently available. For instance, a one centimeter section of a pipe used for pneumatic transport of pharmaceutical powders typically contains a million particles. Several hours of CRAY time is required for this number of particles even for the simplest forcing model. Furthermore, for engineering applications, detailed information of individual particle motion is unnecessary, especially in regions where plug flow or simple shear flow take place. For these two cases, a small sample of particles is enough to obtain the macro behavior of the assembly.

For plug flows, little or no deformation exists in the flow. Computer simulations have been used effectively to determine the shear and bulk moduli as well as heat transfer coefficients in these flows. For simple shear flows, both direct simulation and Monte-Carlo simulations have successfully yielded stress and strain-rate relations. Constitutive equations from these "micromechanical" studies are thus quite established for these two cases. These results have been used to write the field equations for a "continuum" description of granular flows. With a continuum approach, knowledge of an individual particle's motion is no longer necessary. We deal with a small "control volume" instead. This approach enables us to examine flows that have scales much larger than individual particles. Recent developments using the continuum approach are encouraging. Good results for slowly deforming elastic/frictional compact granular materials and fully-developed gravity driven granular flows have been obtained.

The current challenge is to step forward from this basis to deal with industrial flows. In common industrial flows, plug and shear regions coexist in the flow domain. This is further complicated by diverging and converging regions. Interfacing all these regions requires combinations of numerical and theoretical approaches. In this presentation, we begin by reviewing what is known in the constitutive equations for granular flows: the effect of particle properties, sizes, shapes, and hydrodynamic forces. This will be followed by recent studies of transition from "collisional" to "frictional" flows. A framework that connects these results, aimed at producing a computational tool for complicated flow geometry will be presented at the end. This framework will integrate discrete numerical simulations in regions of large gradients and/or diverging/converging conditions with the continuum approach using well-established field equations in regions of either elastic/frictional deformation or fully-developed shear flows.

Pneumatic Conveying of Solids: Flow Behavior and Heat Transfer

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My research group has concentrated its efforts in the pneumatic transport of solids by considering these specific projects:

a) Modeling Gas-Solid Flow in Risers
b) Heat Transfer to Flowing Gas-Solid Suspensions
c) Non-Intrusive Measurements of Particle-Wall Collision Properties

The following discussion gives a brief description of the work we have done or are doing on these projects.

Modeling Gas-Solid Flow in Risers. The flow behavior of a dilute, turbulent gas-solid mixture is modeled. Particle-particle interactions and gas turbulence modulation due to the presence of wakes behind the larger particles are considered. The model captures the flow features seen in the existing experimental data for dilute, turbulent gas-solid flow. It is shown that due to the significant flattening of the mean gas velocity profile with the addition of particles, and the corresponding decrease in turbulent energy production, a generation mechanism must be present in order to produce gas velocity fluctuations which are consistent with the experimental measurements, even in the case where the experimental results indicate a net suppression of gas phase turbulence in the presence of particles.

Currently, we are developing a model to describe the turbulent flow of dense, gas-solid mixtures. The model is based on time-averaging the continuum equations for the gas and solid phases. In addition to the random motion of individual particles (important in dilute phase flow), particle phase turbulence is considered; that is, fluctuations associated with loose clusters of particles which are present in dense phase flow. A speculative closure for this particle phase turbulence is employed by making an analogy to turbulence in a homogeneous fluid.

Heat Transfer to Flowing Gas-Solid Suspensions. Previous extensive experimental measurements of heat transfer rates in turbulent gas-solid flows have conclusively shown the dependence of these rates on the details of the local flow structure, such as the local mean and random velocity components of the two phases, as well as the local solids density. We have developed a mathematical model for heat transfer in particle-laden, turbulent flows which builds on our recent work in the hydrodynamic modeling of dilute particle-laden, turbulent flows. Temperature profiles and heat transfer coefficients are obtained from coupled thermal energy balances for the gas and particle phases. The flow predictions from our hydrodynamic analysis which treats velocity fluctuations in both phases are applied to the heat transfer model. Conduction of thermal energy in the particle phase is augmented due to particle velocity fluctuations.

We are investigating the dependency of the heat transfer rate predictions on the various operating conditions and system parameters such as solids loading, superficial gas velocity, and particle size. Extensive qualitative and quantitative comparisons of model predictions for heat transfer coefficients in vertical tubes are made with a range of experimental data. Preliminary results have shown that for smaller particles at very low solid loadings, a reduction in the heat transfer coefficient, compared to the analogous single-phase flow, is seen.

Non-Intrusive Measurements of Particle-Wall Collision Properties. This project involves non-intrusive measurements of particle-wall collision properties using a particle tracking technique and laser Doppler velocimetry. It has been shown in our modeling work that the degree of particle slip at a solid surface and the magnitude of the particle velocity fluctuations there are highly dependent on these particle-wall collision properties. We have a CRADA (Cooperative Research and Development Agreement) with the Department of Energy and are using the experimental facilities at the Pittsburgh Energy Technology Center - Particle Flow Analysis Laboratory. In the particle tracking technique, the flow is illuminated with thin sheet of pulsed laser light. The collision properties measured are the angle of incidence, angle of rebound, coefficients of normal and tangential restitution and the friction coefficient. The particle tracking technique allows for the measurement of thousands of collisions in a few hours. The particles are injected through a nozzle into a wind tunnel (1 ft $\times$ 1 ft) and collide with a plate placed horizontally at the bottom of the channel. The ambient air flow created by the tunnel assures a minimal slip velocity between the particles and the surrounding air. We are investigating how different types of particles impact surfaces of varying degrees of roughness.

Thus far, we have made measurements involving glass spheres on a glass plate and FCC particles on a piece of a FCC riser wall. The collision properties are considerably different for the two systems. For example, with the FCC system, the scatter in the rebound angle and velocity is much larger than in the glass-glass system, given similar incident and rebound angles for the two systems.

Effects of Particle Properties on the Flowability and Wall Friction of Granular Materials

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The relationships between the bulk mechanical properties of granular materials such as their internal and wall friction angles, cohesion and yield strength are studied extensively and their effects on observed flow patterns and measured wall stresses in silos are well-documented in the various national silo-design codes and in abundance of academic literature [1], [2], [3].

With "real" granular materials such as fossilized fuels, the variations in particle properties such as particle size and shape distributions, particle surface roughness, hardness and moisture content and chemical composition often have a profound effect on the range of values obtained for the bulk mechanical properties during conventional uni-axial compaction and shear cell tests performed on different material samples. In contrast to the popular experimental materials such as glass ballotini or polyethylene beads which have uniform particle properties, it is very difficult to ascribe universal and "generic" values of bulk mechanical properties to different fuels such as coal which can be used to predict reliably the flow behaviour and wall stresses in different silo geometries. A practical albeit empirical solution is possible by testing as many different samples and types of coal and building up an extensive data base of bulk mechanical properties to be used in subsequent design calculations. This is very much the method advocated by the current design codes and much of the bulk solids handling literature [1], [4].

An alternative and a more fundamental approach to "real" granular materials which exhibit a large degree of poly dispersity of particle properties is through a systematic characterization of these properties which require a set of highly specialized microstructural test equipment ranging from electron microscopy for size and shape analyses, micro indentation for surface roughness and hardness, compression tester for the modulus of elasticity to chromatographic and x-ray analyses of chemical composition. Specialized equipment have also been developed to characterize the tribological properties of particles such as single particle shear tester [5] and wear tester [6].

While it is possible to generate vast amounts of data characterizing different material samples, such information is not of much use if fundamental relationships are not established between the measured microstructural properties of different samples and their observed bulk mechanical behaviour which ultimately decides the design and performance criteria for the storage, handling and transport of granular materials.

Furthermore, during bulk storage and handling, dynamic physical processes such as agglomeration, attrition and subsequent segregation of particles are much more pronounced with materials of polydisperse properties which often have detrimental effects on process efficiency (*e.g.* blockage of outlets, intermittent discharge) and product quality (*e.g.* attrition and segregation) in industrial applications. Direct observations of such dynamic assembly behaviour of granular materials necessitate the development and application of novel 3-D flow visualization techniques which allow the measurement of particle velocities as well as interparticle voidage distributions during flow and discharge from model hoppers. At Surrey, the use of gamma ray tomography is found to provide much valuable data on in-situ voidage distributions while tracer tracking techniques are used to provide the necessary information about velocity distributions; [7], [8]. The corresponding wall frictional behaviour is also quantified using dual-axis load transducers capable of measuring simultaneously both the normal and the shear components of the wall stresses; [9].

Continuum mechanical theories of particulate flow in general ignore the particle properties of granular materials and assume constant values of the bulk mechanical properties such as the internal and wall friction angles and cohesion; [3], [10]. In recent years, this shortcoming is being addressed to some extent by the introduction of a variety of explicit constitutive relationships known as "material laws" for more realistic coupling of the bulk stress and velocity fields and spatial variations of the bulk mechanical properties within the flow field are introduced by the use of numerical techniques such as fine element and method of characteristics [11].

In order to investigate the microstructural effects on bulk flow behaviour, it is convenient to adopt a discrete modelling technique which allows for variations in individual particle properties as input data in the numerical calculations. Various 2-D and 3-D computational codes are currently in use based on discrete particle or discrete element techniques [12], [13] which are based on different formulations of interparticle force algorithms. The current work at Surrey is investigating the effects of different normal and frictional force interactions between particles (*e.g.* Hertz-Mindlin, Hooke's Law, continuous potential models) on the resulting velocity and stress distributions in hoppers of different geometries; [14], [15]. In these models, it is possible to vary particle size and shape distributions as well as a range of contact frictional parameters such as moduli of elasticity, interparticle adhesive forces, particle-wall friction so as to establish their effects on the bulk flow and stress fields in silos. Well-known practical phenomena such as blockage of outlet, intermittent discharge, peak stresses at silo walls upon initiation of discharge are produced by computer simulations for comparison with experimental measurements obtained in model silos described above.

Focusing the above approach on the flow of fossilized fuels will require a detailed precursor investigation of the discrete particle properties of fuel samples. These will entail both physical (*e.g.* size, shape, surface roughness) and chemical analyses (*e.g.* mineral content, surface moisture as well as tribological tests such as compression, attrition and wear studies which should enable: i) the ranking of fundamental properties affecting flowability and wall friction and ii) the establishment of upper and lower limits of the parameter values and the functional forms of the limiting behaviour for the range of material samples considered.

It would then be possible to channel the above information into dynamic flow simulations to be conducted in different silo geometries with a view to establish the range of possible flow and wall frictional behaviour representative of different material properties. This is by no means a simple task as it will require substantive development work at the level of interparticle and particle-wall interaction force models in order to include realistic interpretations of the measured particle properties. At the assembly level, to test the statistical reproducibility of the observed phenomena, it will also be necessary to conduct simulations with increasing sample sizes (> 10^5 particles) in different hopper geometries. It is hoped that the in-situ flow visualization techniques currently available will help to reduce much of the speculative nature of the model development by providing a direct route between experiment and simulation.

REFERENCES

[1] Draft Code of Practice for the Design of Silos, Bins, Bunkers and Hoppers (1985) British Materials Handling Board, UK

[2] Roberts A.W. (1981), Bulk Solids Handling, 1 , 747.

[3] Nedderman R.M., (1992), Statics and Kinematics of Granular Materials, Cambridge University Press, UK.

[4] Arnold P., Roberts A.W. and Scott O., (1979), Bulk Solids, Tunra Ltd., Newcastle, Australia.

[5] Mullier M.A., Tüzün U. and Walton O.R., (1991), Powder Tech., 65 , 61.

[6] Mullier M.A., Seville J.P.K., Herbert F. and Adams M.J., (1993), Tribology International, 26 , 329.

[7] Tüzün U. and Hosseini-Ashrafi M.E., (1992), Chem. Eng. Sci., 48, 53.

[8] Nikitidis M., Tüzün U. and Spyrou N.M., "Tomographic Measurements of Granular Flows in Gases and Liquids", (1994), KONA Powder and Particle, 12

[9] Tüzün U. and Nedderman R.M. (1985) Bulk Solids Handling, 3, 117.

[10] Tüzün U., (1985), "Critique of Recent Theoretical Advances In Particulate Solids Flow", Particulate and Multiphase Processes, Edts. T. Ariman and T.N. Veziroglu, 1, 713, Hemisphere Publ.

[11] Drescher A., (1991), Analytical Methods in Bin-Load Analysis, Elsevier.

[12] Walton O.R. and Braun R. L., (1986), J. Rheology, 30, 949.

[13] Herrmann H.J., (1992), Physica A, 191, 263.

[14] Langston P.A., Tüzün U. and Heyes D.M., (1994) Chem. Eng. Sci., 49 , 1259.

[15] Langston P.A., Tüzün U. and Heyes D. M. (1994) Chem. Eng. Sci., "Discrete Element Simulation of Granular Flow in 2D and 3D Hoppers", in print.

Stresses and Flow in Silos

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Introduction. The behaviour of granular materials is very different to that of liquids. Within a granular material both shear stresses and normal stresses exist with well defined regions of slip where rapid movement of the material on either side of the slip plane takes place. The ease or otherwise with which a material can be handled is extremely important. It is essential that the material should flow through the silo and hopper as and when required. Granular materials and bulk solids in general are characterised by a variety of properties including particle size, shape, moisture content, chemical composition, bulk density, internal friction, wall friction, cohesion, tensile strength,*etc*. Modelling the behaviour of a bulk material in a silo/hopper system has been approached in two ways: by considering the material to be a continuum or by considering discrete particle/particle interactions. In the former the individual particle properties are subsumed into parameters taken to represent the bulk properties such as those measured in a shear cell. In the latter particle/particle interactions between regular granular particles are used. In reality the behaviour of a real bulk material is likely to be fully represented by neither of these approaches. Characterising the handlability of a real bulk material, such as a coal, will require both individual particle properties and bulk properties. How such properties depend on the stress state and flow conditions is vital to successful modelling.

Stress Distributions. We have taken the continuum approach and have modelled such situations using the Mohr-Coulomb failure criterion. The stress distributions for the initial fill under static conditions and for the flowing material under dynamic conditions are quite different. The two situations give rise to different stresses on the containing vessel and can give rise to very large values of stress (the so-called switch stresses) at the transition between the vertical wall and the converging hopper. These were modelled and some of the assumptions and implications investigated. Experimental measurements of stress on the walls of a 0.965m diameter cylindrical silo fitted with either a conical or a chisel-shaped hopper were made at the laboratories of the British Iron and Steel Research Association (BISRA) which is now the British Steel Technical Teesside Laboratories. The method has been compared in the literature with the method of characteristics - more sophisticated mathematically but more complex computationally. The simple continuum approach has been found to give a satisfactory evaluation for axi-symmetric and plane geometries and it has been applied to a number of granular materials.

The continuum approach has been extended to the annular region of a silo between the silo wall and an internal anti-dynamic tube. An anti-dynamic tube is a device that may be installed in a silo with the aim of reducing the stresses on the walls by enabling discharge of the material from the upper half of the silo first. The tube extends from just above the hopper outlet vertically upwards to about the middle of the silo. Material discharges through the tube and its momentum prevents material from the region surrounding the tube near the outlet from being discharged. Only when the top section has discharged can the material in the lower section escape. The result is a reduction in the wall stresses. Experimental work was undertaken at the University of Wollongong using a small silo 0.565m in diameter fitted with such a tube. The force on the tube was modelled using continuum methods. Force transducers on the wall of the silo indicated oscillations of the normal force on the silo wall during discharge with amplitude comparable with the mean magnitude of the force. These were particularly noticeable during eccentric discharge of the material.

The extension of continuum models to eccentric geometries in general is being considered.

Flow Fields in Silos: CFD. To determine the flow a constitutive relationship between the stress field and the velocity field is required. Such relationships are well-known for Newtonian fluids. All commercial computational fluid dynamics (CFD) packages are efficient at modelling Newtonian fluids, but each has its own methods of modelling non-Newtonian fluids. We have begun to consider the different non-Newtonian models to see how the choice of model parameters may be made to simulate the flow of a bulk solid. A great advantage of CFD is the ease with which different geometries can be modelled. It is thus well-suited to the investigation of the effects of eccentric silo outlets. The main difficulty is in describing the properties of the bulk solid. However CFD does have the software to model the flow fields provided that an appropriate constitutive relationship can be found. This is a recently started project in which the well-developed software of CFD is being combined with the modelling of granular materials.

Practical Applications: At the present time cohesion, internal friction, wall friction and bulk density are the major factors used to characterise a bulk solid. They are used in the continuum models to predict stress. The development of a Handlability Index to characterise bulk materials such as coal is desirable. It is important that the Handlability Index should be developed in such a way that it can give quantitative as well as qualitative information for use in evaluating the performance of a coal in existing materials handling plant. Information on the mineral content, water content, cohesion and particulate nature of the coal is required to characterise the handlability. We expect to be able to assist in the development of continuum and CFD modelling to incorporate handlability.

Lining Materials. The installation of a new lining material into an existing silo alters the frictional characteristics of the wall. This in turn affects the stress distribution within the bulk material and its flow. We expect to be able to assist in evaluating the effects of a new lining material on stress and flow and to evaluating the forces required to hold the lining in place.

National Responsibility. The author was a member of the British Materials Handling Board (BMHB) committee that prepared: Silos: Draft design code for silos, bins, bunkers and hoppers, published by the British Standards Institute in association with BMHB, 1987. The silo design code was intended as a draft for comment and has been an important part of the British input for the preparation of European (CEN) and international (ISO) standards. The author is also a member of BS Panel on Silos - Handling and Safety. The Panel has been concerned with safety aspects of the installation, operation and maintenance of silos and associated solids handling equipment. It has deliberately avoided specific silo design considerations except where they impinge directly on safety matters.

REFERENCES

Walters, J.K. & McLean, A.C., 4th Intl. Conf. on Bulk Materials Storage, Handling and Transportation, July 1992, Wollongong, "Stresses in a Silo Fitted With an Anti-dynamic Tube."

McLean, A.G. & Walters, J.K., Fourth World Congress of Chemical Engineering, Karlsruhe, June 1991, "Loads in an Experimental Silo fitted with a Tremmie Tube."

Walters, J.K. & Clague, K., J. Powder and Bulk Solids Technology, 2, 1978, 34–37, "Wall stresses in chisel-shaped hoppers containing iron ore."

Walters, J.K. & Clague, K., 1977 I.Chem.E. Symp. Series No. 45, Design Developments Paper G3, 12 pages, "A Theoretical Analysis of Stresses in Wedge-shaped Hoppers."

Walters, J.K., Chem. Engg Sci., 28, 13–21, 1973 "A theoretical analysis of stresses in silos with vertical walls".

Numerical Simulation of Flow Behavior of Granular Solids

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Both continuum and discrete approaches have been used to calculate the behavior of granular solids. Most of the physics that determines the flow behavior simulated by finite element and finite difference continuum approaches is contained in the constitutive models assumed for the material. Unfortunately, there is no consensus among researchers on the most appropriate constitutive model to represent even simple non-cohesive granular solids under a wide variety of loading conditions. Two-fluid continuum models have been applied to fluidized beds with the solid phase represented as a "fluid" employing a constitutive model that approximates the behavior of the granular material (valid as long as the material remains fluidized) [*e.g.*, Gidaspow, 1991]. For particles in suspensions, various models that treat the particles as discrete objects are under development. These models utilize various approaches to model the fluid ranging from finite differencing the Navier Stokes equations (*e.g.*, Tsuji, 1993) to discrete lattice representations (*e.g.*, Ladd, 1994). For quasistatic systems, Stokesian dynamics (*e.g.*, Brady, 1988) utilizes spherical harmonic expansions to approximate the hydrodynamic forces acting on each suspended particle resulting from the motion of all the other particles in the simulated system. Utilization of an effective 'screening length' to limit the range of hydrodynamic forces in such systems has been proposed as a means of obtaining 'exact' solutions for larger systems and at higher Reynolds numbers [Goldhirsch, 1994]. For dry granular flows discrete particle simulation models directly follow all particle trajectories with the bulk behavior being primarily determined by the shape and particle interaction models assumed.

Major advantages and disadvantages of using models that attempt to explicitly track all of the particles include the following:

Advantages:

- Such models explicitly take into account the microstructural nature of the material.
- The physics is reduced to correctly modeling the particle-particle interactions (and/or particle-fluid interactions).
- The collective effects simulated by current discrete particle models match the observed macroscopic behavior of granular media (and suspensions).

Disadvantages:

- Discrete particle methods are computationally intensive, and thus, can only handle problems of limited size.

- There currently is no single standard or accepted interaction model, even for materials as simple as assemblies of cohesionless, inelastic, frictional spheres. (Because of this, novice attempts at such models often neglect important physics in the interactions, like friction and particle rotations).

For dry granular flows such models have been used to verify the predictions of kinetic theory models of rapid granular flows, for simulation of flows in two-dimensional bins and hoppers, and for three-dimensional simulations of gravity flow on inclined chutes and through beds of fixed obstacles (*e.g.* cylinders and spheres). Current models on scientific workstations are routinely simulating systems with on the order of 10,000 particles. A few researchers are doing such simulations with on the order of 100,000 particles (*e.g.*, Hofstetter, 1994). Calculations of a similar nature (*e.g.*, molecular-dynamics simulations) have been reported for systems containing hundreds of millions of atoms on massively parallel machines and researchers at LLNL regularly do such simulations with tens of millions of atoms. Simulations on the same scale are possible with inelastic-frictional particles (*e.g.*, Campbell [1994] recently completed a simulation of a single avalanche with 10^6 discs). To the author's knowledge, there are no current researchers doing such large scale simulations of granular flows (*i.e.*, $> 10^6$ particles). However, because of the nature of strain localization and stress networks during quasistatic deformations in granular materials, it is necessary to include very large numbers of particles in any "representative" sample that attempts to reproduce the bulk behavior of real materials. As parallel processors proliferate we can expect to see a corresponding increase in the number of large scale simulations of granular solids.

REFERENCES

Campbell, C., (Private communication, USC, 1994)

Hofstetter, K., (Private communication, Caterpillar Inc, 1994)

Brady, J. F., "Stokesian dynamics", Ann. Rev. Fluid. Mech., 20, 111 (1988).

Ladd, A. J. C., J. Fluid Mech., vol. 271. 285–309 and 311–339 (1994).

Tsuji, Y., T. Tanaka, and T. Ishida, Powder Technol., 71, (1992) 239.

Goldhirsch, I. (Private communication, Tel Aviv University, 1994)

Gidaspow, D., R. Bezbaruah, and A. Miller in Proceedings of Joint DOE/NSF Workshop on Flow of Particulates and Fluids, Oct. 22–24, 1991, Worcester, Massachusetts, 316–346.

Discussion

The following is a transcription of the final discussion on Tuesday, August 16. The editors have taken the liberty of smoothing the wording wherever they felt it appropriate. Comments have been submitted for approval to those making them. In addition, written comments submitted by several individuals have been included.

Mrs. Evans: I want to say, first of all, thank you to everybody for making such excellent presentations, for your efforts in attending the meeting and for the useful comments made by individuals during the interim discussion periods.

I just want to say a few words about methods of collaboration and the role I would play, in my new capacity of Chairman of the Executive Committee for the IEA[1] Agreement. I see my role very much as a coordinator of information exchange both within the U.K. and between the U.K. and elsewhere. I have access to information on everything that we are supporting on our program. I also know many people doing work outside our program in this area in the U.K. It may be that individual researchers are unaware of the work of other research groups and so I see one of my roles as a source of information on work supported in this area for the U.K. Similarly I offer the information on U.K. projects to the information coordinator in the U.S. Thus the information coordinators can play an active role in encouraging collaboration by identifying groups with similar research interests and placing them in contact with each other. Communication between research groups counts as collaboration.

I feel that the interaction among attendees at this meeting has been very positive. The atmosphere is different from that usually found at an international meeting where people are usually present to promote their own research or department and can sometimes treat the meeting as an ego trip. It has been beneficial to me in that I have seen the different approaches taken by individual researchers to similar problems and am more aware of work going on in this area.

One of the most important comments I noted was from Dr. Walton. He said that one of the problems with modeling in this area is that there are almost as many mathematical models as there are modelers. I think one of the objectives of encouraging collaboration is to prevent this duplication. This should enable research carried out to progress faster and produce success stories that tell of research solving real problems.

The question of industrial versus fundamental research as a topic for collaboration should not really be an issue. The DTI[2] Coal R&D program is geared towards industrial problems and this may provide complementary effort to more academic programs sponsored within other countries. I think Phil Hsieh's concept of the academic idea and the engineering plant as being two distinct things is very important. We should try to encourage a half way point whereby the people involved with the fundamental, highly academic scientific work should try to think about how their work applies to the person with the spanner. Alternatively the person with the hammer or wrench should try to think about the science behind his problem. I think that the research groups involved should be very different. There

[1]International Energy Agency.
[2]U.K. Department of Trade and Industry.

should be one set of researchers trying to find solutions to current industrial problems that could produce success stories relatively quickly. At the same time there should be a parallel efforts where the work is further removed from the industrial problems, but ultimately has a goal and has the chance of being formed into some kind of synthesis. Thus I see the program having several sets of parallel efforts, not necessarily with the same researchers involved in each project. Some teams should address industrial, troubleshooting type projects in order to obtain success stories with which to sell the program. Others should try to work on a goal that will produce results over a longer term.

Dr. Hsieh: I am going to discuss some of my own experience with IFPRI.[3] What they have been doing which I feel is valuable, is that at every annual meeting they arrange for some individuals to make state-of-the-art reviews. They explain just what happened in the last few years in modeling or experimental areas and how they compare and with what implications. I think this has been quite well received. In fact, sometimes there were more discussions out of those questions than individual papers.

Mrs. Evans: In the U.K. we do that as part of our own program development.

Prof. Shen: I have a short comment. One thing I hope not to see it happen is another international meeting. There are too many conferences now and everyone's effort is dispersed too widely. I think if we are going to have a forum, as suggested by people here, it has to be different from those existing international conferences. The thing to do is to have focused topics. They could be a few well-identified industrial problems. Most likely they are interdisciplinary so that every attendee will contribution on different aspects of the same problems. Taking GFARO[4] as a model, it was done very effectively in this way. I think if we are going for such a group effort, then we should first try to define a set of problems now. Then every time we meet, we would define what is the next problem that everyone is going to tackle. Whether there are resources to do that or not I don't know, but I feel that this is the way to do it. We do not want to have just another academic or industrial conference.

Mrs. Evans: That is fair enough and the formation of the program of work from the U.K. for this collaboration is fairly well underway. The intention is that Dr. Tüzün will look at modeling of flow on a discrete particle basis and on flow visualization. Dr. Walters is going to be looking at continuum modeling of stresses; Professor Rotter is going to be looking at a compression tester and a dilation tester and we have another research group in Nottingham that is going to look at another aspect of coal programs. That is what the U.K. brought to the table for this meeting. Any other information on projects supported under our program of work is well on the way to being established and that is what the presenters from the U.K. have tried to say over the last two days.

Dr. Passman: Perhaps I could say something from the U.S. perspective. This meeting came about because of the proposal by ETSU[5] that they and DOE cooperate on a project of this general type. Of course, as you well see and well know, there is tremendous interest in having other countries participate. I hope they will. But just for a moment, speaking from

[3]The International Fine Particle Research Institute.

[4]The U.S. Department of Energy Solids Transport Program Granular Flow Advanced Research Objective.

[5]Energy Technology Support Unit, a contractor to the U.K. Department of Trade and Industry.

the viewpoint of what's going on in U.K. and what's going on in the U.S., the U.K. has their end of this project running, essentially, and it's going to happen. It is very unlikely that we are going to be able to produce any substantial funding in the U.S. for another year, if at all. Intrinsically, the type of effort and the funding for the effort is not going to be the same. I think the thing I have seen in this meeting is that our abilities and interests are highly complementary. There is enough overlap so that we can speak to each other easily. There is enough difference in emphasis so that the sum of the project in the U.S. and the project in the U.K. would be much greater that the sum of the individual projects. There have been several references to our granular flow project in the United States. That project has been very highly interactive. We've had two meetings a year where every principal investigator is required to attend and required to lecture. We have other informal meetings during the year. In addition, either I or somebody from DOE management visits every site every year. There is no way we can do that for international projects and we make no pretense that we will be able to. We would expect that we would have one meeting a year. It would probably be in conjunction with an international meeting that a large number of us would be going to anyway, so it would not be a large additional expense. One of the things we have to think about, something we're probably not going to solve today, is that we do want a constant flow of information exchange and we want a mechanism to do it. It is really not obvious to me what that is going to be. That is something we must work out.

Prof. Goldhirsch: This meeting emphasized capabilities and, as such, it was very different from regular scientific meetings. To me it was a very useful meeting because I learned of some important problems perplexing industry in the field of granular dynamics and, of course, I met some of the best people in the field. If we have further meetings, I would prefer them to be more in the nature of technical workshops. While it is important to have a broad picture of the problems in this or any other field there is no substitute to dealing with the details of the problems encountered both in science and in industry. Some of these were exposed during the meeting. I believe that only by dwelling on details we can truly further and promote the collaboration between science and industry.

In my experience there is a certain problem in communicating scientific results and methods to at least some representatives of industry. One of the reasons for this situation is that the time scale for achieving scientific results may be too long for industry and it is perhaps a good idea to ask our industrial friends to be patient because at least some scientific results may be well worth waiting for. Another problem hampering science-industry contacts or collaboration is related to the fact that models employed or developed by scientists tend to be oversimplified. Such models may not appeal to "practical people", at least at first sight. I believe it is important to explain that many properties of systems are captured by highly oversimplified models. In the language of physics, a complex system may share a universality class with a very simple one. Industry may benefit from results of studies of such models. Input from industry may not only help scientists concentrate their efforts and model building skills in "useful" directions; it may help to modify and fine tune such models to render them of direct relevance to industrial needs. This is why I wish to reiterate the need to discuss technicalities, even boring ones; I believe that the exposition of details can increase the usefulness of meetings such as the present one significantly.

Another point which I would like to mention is that of the importance of numerical studies, in particular that of molecular dynamics simulations. There is a large number of rheological models for granular media, some of which are based on kinetic theory and may be irrelevant in the dense phase while others are founded on continuum mechanical descriptions. I think that it is agreed by practically everyone in this field that we do not really know a set of reliable equations for granular flows. Molecular dynamics simulations, which are now capable of simulating the dynamics of millions of particles, can play a very important role in elucidating the detailed properties of such systems. Their advantage is in the fact that, unlike in actual experiments, one can measure any desired microscopic or macroscopic quality of interest. Simulations are also cheaper than laboratory experiments and orders of magnitude cheaper than industry-scale experiments. They can be used either as a direct tool for investigating the properties of a system of interest or as a means to obtain constitutive relations and effective boundary conditions which can later be used to analyze the properties of granular systems using a macroscopic or continuum description. The only disadvantage of such simulations is in the necessity to define a model of the microscopic grain-grain interactions. I can state, based on experience, that only few properties of the microscopic interactions are important in determining the macroscopic features of the system. This is another manifestation of the concept of universality. Comparison between molecular dynamics simulations and experiment will surely serve to improve the former and help elucidate and/or identify many problems in granular systems. I believe that the final result of such an effort will be a powerful research, design and maintenance tool and, if I may repeat myself, this can be much better appreciated by dwelling on details.

Mr. Salter: Along the line of that thought, I was thinking along the line of continuing the workshop approach. What we have seen in the last could of days is a series of new tools that are available. We can list areas where these tools might be applied individually, or combined and applied. I think your central theme, "Flow of Granular Materials in Complex Geometries," is a good one to continue to focus on. There are potential commercial applications over a wide range of industries. We can pick one or two industrial applications and form small teams or groups to start focusing our effort.

This does not mean that there should be no more effort on "frontier" or "leading edge" areas. Those working in more advanced areas need to stay close contact to those working on direct applications and vice versa so that each can benefit from the other. We at Shell have essentially the same situation. We have some technical staff that are applications oriented and others that are theory and modeling oriented. All are very busy, yet both sides need to keep in close contact to assure that the applied side has the best available technology, and that the modeling/theoretical side is working in areas that are most needed and have the largest positive impact. To achieve the necessary interaction, Shell has formed a corporate wide team comprised of both application and modeling oriented technical staff. The groups are known as the Solids Handling Technical Direction Team. This team meets approximately twice a year to exchange technology, generate a list of needs, and provide technical direction for our research and development programs. Approximately half the team members are permanently assigned to a specific manufacturing location or business. In addition to providing technical support to the major projects organization and Shell's customers, the team members that are centrally located serve as a focal point and resource for Shell locations and businesses that have only intermittent need for solids handling expertise. As a team we select a few (two to five) projects that are generally applicable across the corporation. These projects are selected to advance the technology and improve the efficiency of the team. Each team member works on at least one project and is committed to spend approximately one day per month in support of the effort. By doing it this way, it may take one to two years to complete projects and improvements that might take a few months of concentrated effort. However, without a team effort there has been little or no progress. At this point, slow, steady progress looks good to both those working in the field and to our management.

Mrs. Evans: So how would you envisage the form to these workshops?

Mr. Salter: I guess I would start with a room full of technical specialists, such as this, from industry, national labs and academia, and start brainstorming. There are several techniques for stimulating creative thinking, but the key is that there are no bad or stupid or impossible ideas. The best ideas will stand out and the others will stay on the list until higher priority items are finished or the priority increases. Brainstorming results in a list of ideas and needs that appear at first to be unrelated. Nevertheless, the ideas typically can be organized into a small number of groups that in turn can be focused to key areas of interest or need, and then prioritized based on impact. At this point all the participants are given a change to choose the area in which they would most like to work, or in which they can have the most impact economically, environmentally, or socially. Thus, the large workshop divides into working groups or teams that can develop objectives, action plans and share the work so no one is overloaded. The small teams might meet fairly frequently depending upon progress. The larger workshops would be held less frequently, but are very important for reporting progress, checking priorities are still valid, sharing ideas and stimulating additional thoughts. When the process works well, the results can be quite synergistic.

Dr. Tüzün: This is more of a question than a comment. I want to get clear in my mind whether there is a consorted effort by IEA to establish a number of projects with assigned researchers within a certain time frame which, like the American effort, would be on the basis of regular meetings and inviting roughly the same number of people and having a series presentations of their own work. Because, as Mrs. Evans was saying, the effort in the U.K. is pretty focused, and directed and well defined now. Funding aside, is there an intention on the part of the IEA to pin it down to individual projects and researchers.

Mrs. Evans: The IEA Implementing Agreement is task shared. Thus, each country's program of work, that acts as its contribution to collaboration under the Agreement, is funded by that country. Collaborations between countries then take place in the form of exchange of results, staff, or equipment. No money is exchanged between countries. Effectively the programs of work are already established as projects that are currently supported. That is, those that were not generated specifically for collaboration under the IEA Agreement, work you were doing anyway, can be offered as a contribution to collaboration. The overall aim of this meeting was to discuss how we could generate a large collaboration on the subject of flows of granular materials in complex geometries, using the IEA Agreement as the mechanism for collaboration. This partnership may not necessarily be envisaged as one consolidated project involving teams on opposite sides of the Atlantic, though that would be excellent. The Executive Committee hopes that this meeting will also encourage smaller collaborations on a one-to-one basis.

Dr. Hsieh: I guess you are thinking more in terms of what you are limited to right now. But, can you gradually move into a mode where you are saving a portion of the budget, setting it aside to have a joint focused area in which truly international cooperations can be ventured? I'm not talking about this year.

What is the real goal of this IEA other than individual contacts, which are good? We have to separate this from any other meetings like Particle Technology Forum or some other. There has to be a unique purpose.

Mrs. Evans: My understanding is that it can provide a forum for international researchers to talk about their work without the bias of, say a mechanical or chemical engineering meeting. Though government representatives are usually present at its meetings, the IEA is a autonomous organization and hopes to provide a mechanism for collaboration, through a number of international treaties or Implementing Agreements, on fundamental and near-market energy issues. Therefore with these treaties already in place, there is no need to take part in heavy international legal negotiations before collaborative research can go ahead. The terms and conditions for collaboration are established in the Agreement.

Dr. Passman: Originally, the IEA was formed as a result of the 1970's international oil crisis. The concept was to make the non-OPEC countries much less dependent on the OPEC countries. Numerous other things are being done now. Let's talk about what the strategy of those of us who have thought about cooperating in terms of the multiphase flow agreement. We would like to see an international effort whose results would be greater than sum of its individual parts. Mrs. Evans has been here for several days and we have had extensive discussions. One of the many things we in the U.S. have learned from the U.K. is that they are much better at mechanisms than we are. They are better at dealing with industry, they are more closely connected with their government, and they are better able to coordinate projects because of various legal aspects. I have also had some short discussions with Dr. Ocone and various people from other countries especially during the last week but also during the last couple of months, and their mechanisms are different in yet other ways. An important thing is to learn from one another.

Dr. Ocone: It is not really clear to me at this point what kind of collaboration is possible between Italy and this organization. I don't understand if Italy already was involved in some international multiphase flow project, or not.

Dr. Passman: Not through IEA.

Mrs. Evans: One point one has to remember is that a lot of work is supported that might not necessarily be called multiphase flow research, but contains multiphase flow elements. It depends how you define the focus of the work. We manage the U.K.'s participation in the Agreement as part of the Coal Handling and Supply area of our program. However, much of the work supported in other areas of the program contain a multiphase flow element. For example, in the Advanced Power Generation program area we have a project on pressurized solids transport.

Dr. Ocone: I think that we should be more specific. We don't want to have another meeting like the one. We should discuss in more detail our results and also see the work that has been done to our resources. For instance consider my model. I see my theory and what they really need is just to know how and what the people need and what I can do with my theory; how I can apply the theory. There is a need for more information.

Dr. Peters: The difference between what we are talking about here at this meeting and what we are doing at technical meetings like the one in Denver[6] is to establish and collaborate efforts so that in fact, when you attend a meeting like in Denver, you are actually reporting work that is done collaboratively with somebody else in another country. You would be an author and your counterpart in the U.S. would be an author. You would say this collaboration was under the auspices of IEA. Does that help? That is the difference. This is not a meeting where you are going to exchange technical information. This is a meeting where you are establishing connections that carry on so that you really do collaborative work. So if Otis Walton has a code that is either similar to your code or can help an experimenter in your country with a problem, they start collaborating and they put out the results at a meeting in Denver or one of these other meetings that we are talking about. Hayley Shen said we don't want to duplicate regular scientific meetings and we agree with that. There are too many meetings now for everybody in this room to attend another meeting. I hope that helps a little bit. That is personally what I would like to see come out of all of this. True collaborations where you will actually cooperate, perhaps with joint authors from the U.S., England, Italy, Mexico, and from Norway and maybe all those combined. Ideally, six authors from six different countries.

Prof. Hunt: I think some of these ideas about collaborations from the U.S. standpoint, seems very different from that of the U.K. I don't know if I can speak to all the various U.S. people here, but I can speak for maybe Prof. Campbell and myself. (laughter) I know from our standpoint we are not getting any funding from DOE and that we are not getting any funding from the IEA, and so collaboration for us is impossible unless we take money from other sources to do these kinds of things. So unless there is money available, I don't know how I'm going to be able to do any collaboration or Dr. Campbell is going to be able to.

Mrs. Evans: This Agreement is task shared. The IEA itself does not provide funding.

Prof. Shen: With or without funding, there is no question that this kind of forum will help us promote application of research. This should be without additional cost on either the researchers or the practitioners. It will help us work on focused problems in a concerted way. For instance, if we are interested in studying a problem, through forums like this, we may learn that a slight change of parameters or different configuration can make the study more practical. Then we make those changes. This way we keep our science, but in the meantime we make our study more applicable. In short, we need to talk to industrial people to find out what their needs are. Of course not all industrial problems can be solved by simply changing

[6] The First International Particle Technology Forum, Denver, Colorado, U.S., August 17–19, 1994.

parameters in what we plan to study anyway. Integration of lab and computational work that requires expensive equipment and time consuming code development is an example.

Dr. Walton: There are funding agencies that specifically fund collaborative efforts. For example, NATO[7] has several different programs where they provide funding just to cover collaboration expenses. They will fund the cost of travel expenses and living expenses and things of that sort for collaboration. They do not provide researcher salary or equipment funds for these collaborations. I don't know if IEA sponsorship of a research proposal would facilitate or influence any funding decisions at NATO. One would like to think that if a program like this were highly visible, or if other IEA programs had high visibility in the international community, then receiving endorsement or sponsorship from the IEA subcommittee might actually help in getting approval for collaboration funding from NATO. I don't know if this is the case or not.

Mrs. Evans: We are in a chicken and egg situation here because it is difficult to raise the profile of the IEA Agreement unless we have collaboration and we cannot have collaboration unless we have a high profile IEA Agreement. You have to start somewhere and this is where we have started.

Dr. Passman: Just from the interactions at this meeting, it is clear that we are seeing collaboration coming, whether we like it or not.

Dr. Hsieh: We have got to provide some incentive, however small it is, for people to initiate collaboration. Travel money is certainly part of it. Maybe by joining with NSF, DOE could do something.

Dr. Walton: NATO has several programs and they fund a significant number of people each year. It is not a lot, but hundreds of people a year are funded under these NATO programs.

Dr. Ocone: I know there are special programs for cooperative research among people from NATO nations who are trying to develop international cooperation.

Dr. Hsieh: I think this probably should be some sort of special interest group, that you have some areas identified so that we all come to this meeting with specific science and technology in mind. Define certain areas.

Prof. Goldhirsch: Maybe it is better instead of lectures just to have some posters and give ample time to people to discuss rather than sit down and listen to people lecturing. It might be more helpful. Instead of sitting in lectures we might probably prefer to talk to each other.

Dr. Passman: I think, Mrs. Evans correct me if I am wrong, the U.K. has made a decision that hoppers are things to work on.

Dr. Peters: What is a hopper? Is a hopper part of a silo?

Prof. Rotter: One of our difficulties in the field of bulk solids storage is that researchers and engineers use different words to describe these structures. Some people in Britain use the word "hopper" to mean an entire storage structure, but this is non-standard. The complete silo may be called a silo, bin bunker, or containment structure. Personally, I would like to see us all using the term "silo" to mean all kinds of complete storage structure, and the term

[7]The North Atlantic Treaty Organization.

"hopper" to mean only the converging section at the bottom, in which solids accelerate towards the outlet. The term silo is international, as the word has ancient Greek origins, and has the same meaning in French, German, Italian and Danish, to name a few languages.

The key feature of the hopper is that it is the converging section at the bottom of the silo. The solids usually pass through the hopper by gravity feed alone, and must undergo major particle rearrangements to achieve it. Hoppers cause three main kinds of problems: first, the hopper may collapse because pressures from the granular solid exceed the strength of the structure; second, the granular solid may hang up in the hopper, causing arching or ratholing; and third, the granular solids flow pattern, which is strongly influenced by the geometry and surface of the hopper, may cause segregation of the solids. These three problems are the more focused targets of research on hoppers.

It is not clear that granular solids dynamics (DEM) can tell us anything useful about the first two. The third depends on may factors, so that we are still far from being able to model the behavior well: particle size distribution, particle surface roughness, anisotropy of particle shapes and packing, filling processes into the silo, inhomogeneity in the particle packing and orientations, local variations in wall surface roughness and wall geometric imperfections certainly all have a role. There is a long way to go here.

Dr. Passman: Dr. Peters came to me a couple of years ago and said we ought to be working on problems in bins and hoppers. There were two motivations. One was that they are of great importance in the coal industry. The other was our interaction with Sunil de Silva[8] who I think is doing spectacular work in this area. My reaction was that we were not ready to do that kind of work yet. I have been thinking about these problems ever since that conversation. I feel we may be ready to do good work on them at this point. The real scientific problem, as I see it, is that for fast flows there is a theory. It is not perfect, but it is a good working theory. We know very little about statics. We know almost nothing about the intermediate regime and we are pretty ignorant about transitions from statics to dynamics. Nonetheless, maybe we are ready to start working on that. Could we, perhaps, come to some agreement that would be an area of mutual interest among the parties at this meeting?

Prof. Rotter: I think that is a very limited view of what has been achieved and what can currently be done for silos and hoppers. There is an enormous body of work on models applicable to static conditions. In general, these are continuum models, but the test for the quality of a model is not its elegance but its ability to predict observed behavior, based on limited measurable data about the granular material and the container. It is not a damning criticism of a continuum model to say that it is semi-empirical or based on the matching of mathematical relations to experimental observations, within the constraints of physical laws. These continuum models are excellent for predicting many aspects of silo and hopper behavior, and it is continuum models which permit us to design storages at the present time. We may have many failures, but these failures are a tiny percentage of the whole, and the use of continuum theories to design silos will continue for a very long time to come. My concern at this meeting is to ask why you are doing all this work on discrete particles. What

[8]Prof. Sunil R. de Silva, Powder Science and Technology Research A/S, Porsgrunn, Norway.

is it for? As noted above and in a slide in my talk, I tried to show that there are three principal problems in silos, from the point of view of granular solids (not structural strength). These are the flow-no flow criterion; segregation of the solids; and the pressure regime leading to structural failures. Put more bluntly: will the stuff flow or not; will it remain uniform; and will the hopper fall off?

These three questions need different approaches. The question of flow or no-flow depends on arching and/or ratholing in the silo. These conditions leave a large mass of static solid in the silo, and it should be predictable in its final state as a static condition. We know that it is sensitive to the stickiness of the solid, often associated with the moisture content, so a DEM model for it must be able to include interstitial moisture in some way. Current design is based on static continuum theories, and these appear to be much more appropriate.

The flow rate is an important question under the heading of the flow-no flow criterion, but in practice flow rates are commonly governed by the speed at which a feeder operates beneath the hopper, not by the free fall of solids through a hole.

Segregation is a granular solids dynamic phenomenon, and well suited to DEM. Finite element models appear to be pretty useless here. The question of structural collapse is much more complicated. It is certainly important that we understand the pressures exerted on silo walls by the granular solids, but these themselves are not enough. The pressures are applied to a complex thin-walled shell structure, and a high pressure is not necessarily a bad thing. There are several instances where a high pressure makes the structure stronger and less likely to collapse, rather than the reverse. Thus, if the work is focused on pressures in silos, it is quite important to have a good understanding of the structural response, and of structural failure criteria.

The numerical and theoretical predication of pressures in silos is a big problem for a number of reasons. The really damaging pressure regimes in silos are unsymmetrical and occur in the early stages of discharge. The flow pattern is very important. Anisotropic and inhomogeneous responses in the solid, together with wall irregularities have been shown in experiments to matter greatly. These are phenomena which neither DEM nor FEM can successfully address at the present time. DEM has difficulty in modeling an adequate number of realistic particles, and its pressure predictions tend to be rather primitive at present: FEM has difficulty in modeling rupture surfaces, small outlet openings, and all but the first of discharge.

There are lots of opportunities for good scientific work on different aspects of the hopper problem, and several different approaches which can be valuable when applied appropriately. The solutions to these problems have great industrial relevance.

<u>Dr. Passman:</u> I have to apologize. My background and what I still consider to be my trade is theoretical mechanics and you have to take some things I say with a little grain of salt. "Solved" may mean something different for me than it does for others.

<u>Prof. Rotter:</u> I think I'd like to hear what the industrialists feel about my listing of the three questions with regard to hoppers.

<u>Dr. Hsieh:</u> It is the area in, about, or around the silos. I think those are the issues. Whether

it is going to flow or not and if it flows how well it flows. Another issue is the possible damage to the silo structure. I'm not saying that the last issue is one of the most important ones to Alcoa, but that certainly is quite relevant. What happens inside the hopper is important.

Dr. Campbell: Dr. Passman, maybe when you talk about reticence about doing hoppers because we don't know about transitions and all this, perhaps the first step is to work on statics and transitions without trying to go all the way to the end.

Dr. Passman: My guess is that is doing all of the necessary science would take us another ten years. We have to find a middle road, where we do the pure science and work on the practical problems simultaneously. The advantage of an integrated project would be that practitioners of each art could take advantage of one another's successes and failures. This could accelerate the success of each art. The whole would be greater than the sum of the parts.

Dr. Walton: Dr. Passman, I think you will find that a large segment of the granular flow community is not well represented at this meeting, or perhaps, anywhere in the U.S. In Germany, and I think in the U.K., they are already successfully doing finite element calculations of granular flows. In the U.S. there is only a little of this work being done, and it is mostly looking at flow initiation (that is, whether or not material will start to flow), not examining steady state flows. The Germans have finite element models that they feel comfortable with for certain conditions. We don't do much of that. A little finite element modeling of granular flow was started in this country nearly 20 years ago, by Bill Pariseau at University of Utah, for instance, but it has not been followed through to any great extent.

Prof. Tüzün: I know for a fact that there are a number of institutions in Germany, for example, who have been producing substantial results on the statics and the transition from statics to dynamics using finite element techniques and the interaction between the flow and the structures. For example, these are in the University of Karlsruhe and also in Braunschweig so there are a number of centers of finite element excellence in Europe and in the U.K. We are liaising with these people under the Euro-Silo program.

Dr. Passman: We've been working on getting Germany to join in this effort formally or informally since long before the start of my work in the IEA in 1992. In fact I asked Kolumban Hutter[9] to come to this meeting. He expressed a definite interest, but by the time I got around to asking him it was just too late for him to do so.

Dr. Tüzün: There is virtue in getting involved along the lines of sort of collaboration we are envisaging within the Euro-Silo program. The finite element input is going to come from them into that program and some effort also from the French.

Dr. Passman: I would like to thank all of you for attending this meeting. Many of you came with no financial support, just with the selfless purpose of helping decide on the direction of research in fossil fuel multiphase flow sciences. You have done an excellent job, and I think that we have had wonderful and useful interactions with one another. Such meetings on the philosophy of engineering science by engineering scientists are much too rare.

[9] Prof. Kolumban Hutter, Technische Hochschule Darmstadt, Germany.

Dr. Fukushima and I as local organizers wish to express our personal thanks to all of you. I am sure that I speak for the Executive Committee of the IEA Fossil Fuel Multiphase Flow Sciences Agreement, Mrs. Evans, Dr. Peters, Mr. Ronold, and Prof. Shook, in thanking you also.

At this point, the formal end of the meeting was called. Some individuals remained for further informal discussion and for a tour of The Lovelace Institutes Nuclear Magnetic Resonance Imaging Laboratories.

Additional Comments

This commentary was submitted in written form.

Areas for Further Research:
Coal Flow Through Complex Geometries
J. Peace
British Steel

- Coal flow down chutes
  What conditions cause blockages?
  What conditions promote flow?
  (Can this be computer simulated Campbell/Goldhirsch)
- Rapid and reliable coal characterisation
  Predict coal flow and bunkering characterization (Rotter/Melany Hunt)
- Through-life coatings of lining systems and insight into new mechanisms – could save "£M" (Walters/Jennifer Sinclair)
- Pressures in complex geometries to determine lining installation systems (Bunker & chutes) (Rotter/Mena)
- Effects of vibration to promote flow. What "Q value", amplitude and frequency include segregation and degradation. (Malchett/Hunt)?

The next 12 pages are copies of material presented by J. Salter of Shell Development Company.

Solids Handling Technical Direction Team

Westhollow Technology Center
August 15, 1994

1993 Highlights

- Demonstrated need to maintain solids handling skill within Shell.
- Obtained Chemical Business Center, Head Office and location management support.
- Established SHTDT comprised of representatives/contacts from all Chemical businesses and location.

Team Formed

K. G. Anderson - WTC/Gran-Flow
P. C. Becker - NMC/Taft *
J. C. Ginestra - WTC/Multi Ph.
J. Horzelski - NMC/HPRU *
P. C. Lewellen - WTC/Comp. FM
Q. T. Nguyen DPMC/Resins *
R. A. Parker - WTC/Chem. Dev. *
L. E. Stein - WTC/Solids Sep.
W. H. Watson Argo Plant *

R. M. Bass - WTC/Systems
Y. Chen - WTC/Fluidiz.
R. D. Harris - WTC/Poly. Proc. *
R. R. Jean - WTC/Multi-Phase
K. F. Malinowski PET Akron *
J. Ostergaard - BEP/Elastomers *
J. A. Salter - WTC/Team Ldr. *
J. G. Tunnell - WTC/Sol. Hdlg. *

- Most activities closely integrated with mainstream activities.
- Resouce commitment is limited one day per month not related to mainstream activities.

Vision

Our vision is to achieve:

- safe,
- effective,
- reliable

use of solids handling equipment and technology to produce:

- high quality,
- cost effective

products that meet and exceed the demands and expectations of our customers, and

to be recognized as providing a valuable service to both our internal and external customers.

Mission

Our mission is to provide in-depth office and field engineering support to facilitate:

- continuous, and
- practical

technical improvements in solids handling to meet the goals and objectives of Shell's businesses.

Our customers are:

- Product locations,
- E&P Locations,
- Business Centers,
- Major Projects Organization,
- customers of Shell products, and
- other Shell Development Departments.

Scope

Solids handling encompases:

- particulate solids,
- gas or liquid environments,
- all equipment and processes, and
- all temperatures and pressures.

Various individuals support specific businesses.

1994 Milestones

- Pneumatic Conveying
- Erosion Mitigation
- Particle Attrition
- Solids Characterization
- Solids Separation

Summary

The Solids Handling Technical Direction Team has:

- **just begun,**
- **made good progress, <u>but</u>**
- **has a <u>LONG</u> way to go.**

Attachment 2
Solids Handling Technical Direction Team

Areas of Interest

Table 1
Identified Problem/Opportunity Areas

1. Pneumatic Conveying
   - a. How to Design a System
   - b. Basis for Decision Making
     - i. Dilute Phase
     - ii. Dense Phase
       - (1) Batch
       - (2) Continuous
     - iii. Line Stepping vs. Staged Injection
     - iv. L/R Bends vs. Conveying Elbows
     - v. Snake Skin
     - vi. Erosion/Attrition
     - vii. Electrostatics
   - c Models/Tools
   - d Specifications/EGGS
2. Solids Characterization Data
   - a. Properties
     - i. Physical
     - ii Solids Flow
     - iii. Chemical
     - iv. Explosivity
     - v. Electrical
   - b. Standard
     - i. Methods
     - ii. Laboratory Qualification
   - c. Common Access Database
3. Contractor Interaction
   - a. EGGS
   - b Qualification
     - i. General
     - ii Specialty Solids Handling
4. Sampling
   - a Protocol for Representative Sample
   - b Statistical Tools
   - c Automatic/On-line
     - i. PSD
     - ii. Specific Gravity
5. Separations
   - a. Cyclone/Hydroclone Design
   - b. Filter Design
     - i. Gas/Solid
     - ii. Liquid Solid
     - iii. Bag Material Durability
     - iv. On-line Cleaning
   - c. Centrifugation
   - d. Elutriators
   - e. Safety
   - f. Environmental
6. Instrumentation
   - a. Level
   - b. Inventory Tracking
   - c. Mass Flow Metering
   - d. Solid Concentration
   - e. Electrostatic Charge Generation
   - f. Gas Composition (e.g., O_2 content)
   - g. Moisture Content
7. Blending
   - a. Gravity
   - b. Mechanical
8. Storage
   - a. Reliable Discharging
   - b. Segregation
   - c. Inerting
   - d. Cooling
   - e. Stripping
9. Other
   - a. Packaging
   - b. Drying
   - c. Fouling
     - i. Compressors
     - ii. Heat Transfer Equipment
   - d. Valves
     - i. Gas Tight
     - ii. Reliability

Each of the team member voted for the three most important areas or area of highest need. The areas identified by this process were: pneumatic conveying, solids characterization, contractor interaction, solids separations and sampling. The first two areas were then discussed in detail and the following goals/action plans we agreed to. The goals/action plans for the last three areas were deferred to working groups of interested individuals. Although it was agreed that manpower limitations might make it difficult to address adequately all five areas in 1994 and that some actions may be deferred until 1995, the items are so closely linked to customer driven activities that there will be identifiable goals what can be completed during 1994.

1994 Goals:

Pneumatic Conveying Goal Statement:

1. Provide Team members and their customers with computational tools and information they need to design, trouble shoot, operate and maintain their pneumatic conveying systems. By the end of 1994 to:

   - have a plan and a prototype model, and
   - provide guidelines for use and validity of the prototype model.

2. Provide Team members and their customers an implementation plan and a prototype EGGS for at least one type of pneumatic conveying system.

   Working Group: JAS/YC (co-leaders), PCB, JH, KFM, QTN, JO, RAP

Solids Characterization Goal Statement:

Provide Team members and their customers the solids characterization information they need to design troubleshoot, and maintain their solids handling systems. By the end of 1994 to:

- have a plan for implementation and a prototype for acquiring, storing and communication solids characterization data, and
- qualify at least one laboratory for characterization of at least one property.

Working Group: JAS (leader), RMB, PCB, QTN, JGT, RAP

Contractor Interaction Action Plan:

Define goals and propose plans of action.

Working Group: JGT (leader), KFM, QTN, JO, JAS (Gerry Wise - Project SAS?)

Solids Separations Action Plan:

Define goals and propose plans of action.

Sampling Action plan:

Define goals and propose plans of action.

Working Group: RAP (leader), JH, BEP representative

DEFINITION/SCOPE OF SOLIDS HANDLING SKILLS AND HARDWARE

Services Provided

The following table is a list of the types of service that SHTDT can provide technical support to Operations and the Major Projects Organization. The list is not exhaustive, but is reasonably comprehensive.

Table A
Typical Engineering Services Provided

Hardware Related Services (particulate solids, wet or dry)	Process Related Services (particulate solids, dry or wet)
Mechanical Design	Basis for Design
Specification	Detail Process Design
Control Logic Sequencing	Process Flow Diagram
Vendor Qualification	Piping and Instr. Diagrams
Vendor Selection	Control Logic/Sequencing
Acceptance Testing	Commissioning
Commissioning	Startup
Startup	Debottlenecking
Debottlenecking	Optimization
Optimization	Problem Solving
Problem Solving	Failure Cause Analysis
Failure Cause Analysis	Solution Development
Solution Development	Solution Implementation
Solution Implementation	Research
Research	Development
Development	
	Other Services
	Technical Assurance (related to services provided)
	Third Party Contracting and Administration
	Training
	Team Leadership

Typical Solids Handling Hardware

The following table is a list of the types of equipment for which SHTDT can provide technical support to Operations and the Major Projects Organization. The list is not exhaustive, but is reasonably comprehensive.

Table B
Typical Solids Processing/Handling Hardware

Agglomeration
    Chemical
    Mechanical
        Pelletizing
        Briquetting
Blending
Conveyors
    Belt
    Drag
    Pneumatic
    Hydraulic
    Screw
    Vibrating
Dewatering
Devolatilizing/Drying
    Conductive
    Convective
    Microwave (RF)
Mixing
    Gas-Solids
    Liquids-Solids
    Solids-Solids
Packaging
    Bagging
    Baling
    Boxing
    Semi-bulk
    Bulk
Pressurization/Depressurization
    Control Valves
        Fluidic
        Mechanical
    Lock Hoppers
    Wear Pipes
	Reactor Design
	    High Pressure
	    High Temperature
	    Plug Flow
	    Stirred
	    Unstirred
	Screening/Filtering
	Separation Processes
	    Filters
	        Gas-Solid
	        Liquid-Solids
	        Liquid-Liquid
	    Centrifuges
	        Gas-Solid
	        Liquid-Solids
	    Cyclones
	        Gas-Solid
	        Liquid-Solids
	    Screening Device
	        Gyratory
	        Oscillatory
	        Rotating
	        Stationary
	        Vibrating
	Size Reduction
	    Cutting
	    Crushing
	    Delumping
	    Milling
	    Attrition
	    Sizing

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