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GRANULAR FLOW CONSIDERATIONS IN THE DESIGN OF A
CASCADE SOLID BREEDER REACTION CHAMBER

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Abstract

Both horizontally and vertically oriented rotating chambers with granular material held on the inner surface by centrifugal action are examined. Modifications to the condition for controlled quasi-static flow on an incline plane, $\phi_w < \alpha < \phi_r$, where ϕ_w is the wall friction angle, α is the angle of inclination of the plane, and ϕ_r is the drained angle of repose of the material are examined for the case of horizontal and vertical surfaces of revolution. Allowed included half angles for horizontally oriented chambers are likely to be in the range of $30^\circ \pm 10^\circ$ for ceramic particles and metal surfaces. For vertical orientations the maximum half-angle of the top cone is slightly less than the wall friction angle ϕ_w while the lower portion can have a half angle as large as $(90^\circ - \phi_w)$. Percolation of fines through shearing granular solids is briefly discussed and recommended experimental and calculational studies to obtain a better understanding of this behavior are described.

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GRANULAR FLOW CONSIDERATIONS IN THE DESIGN OF A
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INTRODUCTION

The CASCADE centrifugal-action flowing solids concept (J. Pitts, 1983) has several potential advantages in terms of safety and efficiency over alternate designs under consideration employing flowing liquid metal for the first wall of an inertial fusion reaction chamber (J. Pitts et al., 1982). In order to evaluate the feasibility and economics of such the CASCADE concept we need to carefully examine the solids flow phenomena involved. Even though a great many empirical engineering studies have been done in the past century, the flow behavior of granular solids is not a well developed science. Research is currently underway at various universities (and at LLNL) to understand the behavior of simple assemblies of equal size spheres. The flow behavior of material with a wide size distribution and assymetric shapes is even further from being fully understood. However, because of the studies that have been conducted, we know qualitatively a few things about flowing solids and can use this knowledge to at least qualitatively put some limits on the types of behavior to be expected in a CASCADE flowing solids blanket design.

Figure 1 shows a schematic of the CASCADE design concept (from Pitts, 1983) in which Li_2O pebbles are fed into the ends of a rotating chamber. Centrifugal forces keep the pebbles on the surface and cause them to flow "down" to the larger diameter central region where they exit into a stationary catcher. The following pages outline some of the basic flow phenomena involved and some of the unique problems of the centrifugal-action flow being considered.

NATURE OF THE FLOW

At least two significantly different types of flow are possible with granular materials: supercritical flow in which the velocity of the flowing material is higher than the propagation velocity through the bulk granular material, and subcritical or quasi-static flows in which disturbances can be propagated upstream. In supercritical flow granular materials behave very much like fluids and much of our intuition and understanding of fluid flow can be applied directly to such granular flows. For example, the velocity of such flow would increase if the slope of the incline is increased and would likewise decrease as the slope decreases. Sub-critical flows on the other hand can exhibit behavior significantly different from "normal" fluid flow behavior, specifically, the flow rate can be totally controlled from a downstream position, making it possible to stop the flow while the material remains on the incline. Transitions from super-critical to sub-critical flow result in granular jumps. (Such transitions are currently being studied at Cal Tech under the direction of Prof. C. Brennen. Also, Prof. S. Savage at McGill University, has examined such transitions, initiating them with small perturbations on the lower flow surface [Savage, 1979]). The quasi-static type of flow observed when the total flow rate is controlled at the bottom of the incline has several features that can be beneficial in the design of a Cascade reactor. The appropriateness of considering quasi-static flows can quickly be checked by considering the $2 \text{ m}^3/\text{sec}$ pebble flow rate, suggested by Pitts (1983), which would result in an axial velocity of only 0.03 m/sec near the exit of the Cascade reactor where the total flow area would be nearly 60 m^2 . This is clearly far from propagation velocities even in loose porous assemblies of particles.

Fig. 1. Schematic of Cascade: A centrifugal-action solid-breeder reaction chamber (from Pitts, 1983a).

INCLINE PLANE FLOW LIMITS

For cohesionless granular materials the total mass flow rate can be controlled at the bottom of an incline plane over which the material is flowing if the following conditions are satisfied

$$\phi_w < \alpha < \phi_r \quad (1)$$

where α = angle of incline

ϕ_w = wall friction angle (above which sliding will occur)

ϕ_r = drained angle of repose for the material

An example of this situation is illustrated in Figure 2 where rubblized oil shale is sitting on an incline plane on an angle (30°) well above the wall friction angle (25° to 28°) but prevented from flowing by a small shelf at the bottom of the incline. Additional material at the top does not force flow in this situation because the maximum flow depth is controlled by a wier or gate of fixed depth. The drained angle of repose, ϕ_r , is the natural slope of the material remaining after flowing over an edge or through an orifice. This is illustrated in Figure 3 where material has been removed from the lower incline and the top surface is at angle, ϕ_r , with respect to the horizontal. If the conditions (1) are satisfied we can separately control the flow depth (at the top of the incline) and the flow rate (at the bottom of the incline) without any active feedback mechanisms. Figure 4 is an example of just such a situation operating on an incline with $\alpha = 35^\circ$, just slightly below the angle of repose for the material, $\phi_r = 37^\circ$. In Figure 4a the flow is temporarily stopped and in Figure 4b the material is flowing through an orifice of controlled width at the bottom of the incline. The depth of material on the incline is approximately the same in both situations indicating that control of the depth is independent of the flow rate control.

Fig. 2. Example of flow stopped by downstream condition (a shelf), with depth controlled at top.

Fig. 3. Illustration of drained angle of repose, ϕ_r .

Fig. 4. Example of quasi-static granular flow in which the flow rate is controlled at the bottom of the incline while the depth is controlled at the top.

Such flows appear to be ideal for Cascade reactor purposes so it is appropriate to examine the restrictions imposed by relation (1) on the design of the Cascade vessel. The wall friction angle depends on both the granular material and on the wall surface material. This angle is likely to lie in the range $24^\circ < \phi_w < 32^\circ$ for ceramic particles on a machined metal surface. The drained angle of repose for the material depends on the size and shape distribution of the particle as well as on their surface properties but is likely to lie in the range $30^\circ < \phi_r < 40^\circ$. Thus we will probably find a quite limited range of angles for α that will satisfy relation (1), (likely to be in the range, $\alpha \sim 32^\circ \pm 8^\circ$). In a centrifugal action vessel the effective angle of the incline, α , can be measured with respect to the total body force acting on the material, gravity plus centrifugal forces.

EFFECTIVE ANGLE OF INCLINE FOR HORIZONTAL AXIS CONE

Consider a cone rotating about a horizontal axis as shown in Figure 5. The total body force acting on the material is the sum of gravitational, centrifugal and coriolis forces. For a particle stationary on the inside surface of the rotating cone the coriolis force is zero and the effective body acceleration, $\vec{g}_{eff}$, is just the vector sum of the acceleration of gravity, $\vec{g}$, and the centrifugal acceleration, $\vec{a}_c$.

$$\vec{g}_{eff} = \vec{g} + \vec{a}_c$$

In the laboratory frame of reference $\vec{g}$ is a constant vector pointing downward and $\vec{a}_c$ has constant magnitude but rotates about the axis always pointing

Fig. 5 Effective body force, g_{eff} , acting on material on the inside of a cone rotating about a horizontal axis.

view from rotating particle
($\theta = \theta_c$)

$\vec{v}_c$ plane normal to cone axis

radially outward. Viewed from the point of view of a particle on the rotating cone the centrifugal acceleration, $\vec{a}_c$, is constant always pointing "down" (i.e., radially out) and the gravitational acceleration appears to have its direction rotate, always remaining in a plane perpendicular to the axis.

In examining the driving force for flow "down" the incline we can look at projections (i.e. components) of the total effective body force, g_{eff} , along the surface of the cone in both the axial and the circumferential directions. First, consider the magnitudes of the total effective body acceleration in the radial direction, $\vec{g}_r$, and in the circumferential direction, g_θ , given by

$$g_r = \vec{a}_c + g \cos\theta = \omega^2 r + g \cos(\omega t) \quad (2)$$

$$g_\theta = g \sin\theta = g \sin(\omega t) \quad (3)$$

where the angle θ is the current orientation of the point on the rotating cone, with $\theta = 0$ corresponding to the bottom.

AXIAL FLOW

Axial flow should be primarily determined by the component of the effective body force in the direction perpendicular to g_θ and along the surface of the cone (i.e., down the incline). Since g_θ is perpendicular to this direction it does not contribute directly to flow in that direction and we thus need to examine the projection of g_r along the axial surface of the cone, g_a .

$$g_a = g_r \sin\alpha = [\omega^2 r + g \cos(\omega t)] \sin\alpha \quad (4)$$

The corresponding normal force, g_n , given by

$$g_n = g_r \cos \alpha = [\omega^2 r + g \cos(\omega t)] \cos \alpha \quad (5)$$

varies in magnitude exactly in phase with the shearing force so that the axial flow stability limits should be exactly the same as observed for incline plane flow, i.e., equation (1), provided that ω is large enough that $\omega^2 r > g$ for all r under consideration.

John Pitts (1983b) recently conducted some flow tests on the inside of a small rotating cone and found that flow occurred at angles of inclination, α , lower than those predicted by relation (1). For example, he observed flows at inclinations of 20° when the wall friction angle measured on a flat incline was close to 30° . The key to understanding why he obtained flows at lower angles of inclination than expected lies in the neglected circumferential acceleration, g_θ , given by equation (3). If we compare equations (3) and (5) we see that the ratio of normal force, g_n , to shearing force in the circumferential direction, g_θ , is not constant but varies with orientation angle as a point rotates about the axis. In order to determine whether material will slide or not we need to compare the total shearing force to the normal force to see if it exceeds the tangent of the wall friction angle, $\tan \phi_w$.

The total shearing term is the vector sum of the g_θ and the g_a terms and has a magnitude, g_s , given by

$$g_s = \sqrt{g_\theta^2 + g_a^2} \quad (6)$$

We have already examined the axial component, g_a , of this surface shearing term now consider the circumferential component, g_θ . (e.g., we can think of this as considering the case where $\alpha = 0$ so that g_a is identically zero by equation (4)). In this case we find that the material will periodically exceed the wall friction limit, ϕ_w , whenever the ratio g_θ/g_n exceeds $\tan \phi_w$ and we can expect to see circumferential sliding initiated, i.e., when

$$\tan \phi_w < g_\theta/g_n \quad (7)$$

or

$$\tan \phi_w < g \sin \theta / (\omega^2 r + g \cos \theta)$$

At values of $\theta = 0$, and π , g_θ is zero and no circumferential sliding occurs but at angles of $\theta = \pi/2$ and $3\pi/2$ this ratio reaches a maximum value given by

$$\left. \frac{g_\theta}{g_n} \right|_{\max} = \pm \frac{g}{\omega^2 r}$$

Thus whenever $\tan^{-1}(g/\omega^2 r) > \phi_w$ we can expect to see periodic circumferential sliding - oscillating back and forth as the rotation proceeds. In terms of the test John Pitts performed where the wall friction angle was near 30° , we would expect to see some circumferential sliding for any rotational speeds where

$$\omega^2 r \leq 1.73 g.$$

In addition to this circumferential term there is also the previously considered axial term, g_a , to account for. In order to determine if the material will slide on the walls we need to compare the ratio g_s/g_n to $\tan\phi_w$ with g_s given by equation (6) and g_n by equation (5).

It should be noted that for any finite inclination angle, α , we can expect to see some sliding occurring along the axis if the total slip criterion is exceeded since at least a small component of that motion will be axial. For a fixed rotational speed the value of $\omega^2 r$ will increase as one moves down the incline so that the slip criterion may allow sliding periodically at the small diameters but not allow sliding at the larger diameters. Thus we can expect to be able to use flow criteria quite similar to those for incline plane flow in regions where the centrifugal acceleration greatly exceeds the acceleration of gravity (i.e., at large radii) and can expect to see flow occurring at significantly smaller angles of inclination when the centrifugal acceleration is closer to magnitude of the earth's gravitational pull (i.e., near the inlet radius of a Cascade reactor). The net effect of the periodic circumferential flows on a full scale Cascade design will probably be a slightly thinner layer on the top of the cone especially in the small radius portion near the inlet. This will occur because in all cases any circumferential sliding that occurs tends to move material toward the lower half of the cone.

In summary, a Cascade chamber rotating around a horizontal axis can have controlled quasi-static flows over a limited range of angles (corresponding to cone half-angles not too different from 30°). The actual limiting angles are somewhat shallower than predicted by incline plane flow but will approach the incline plane values near the large radius exit.

VERTICALLY ORIENTED CASCADE CHAMBERS

Centrifugal action can also be applied to vertical axis chambers, and criteria for controlled quasi-static flow for this orientation can readily be derived. The analysis of limiting flow conditions is somewhat easier in a vertical orientation since there are no oscillating acceleration components. Consider first a rectangular cylinder rotating about a vertical axis as shown in Figure 6. In the reference frame of a particle rotating on the inside of the cylinder the centrifugal acceleration is a constant vector always pointing in the radial direction with magnitude $a_c = \omega^2 r$, while the gravitational acceleration is a constant in the axial direction. The effective angle of inclination of the inner surface, α_{eff} , can be measured from the normal to the total effective body

Figure 6a

force acting on the particle, $\vec{g}_{eff}$,

$$\vec{g}_{eff} = \vec{g} + \vec{a}_c$$

Since both $\vec{g}$ and $\vec{a}_c$ are constants for a rotating cylinder we find that controlled quasi-static flow is achievable for effective angles of inclination, α_{eff} , in the range

$$\phi_w < \alpha_{eff} < \phi_r \quad (8)$$

$$\text{where } \alpha_{eff} = \tan^{-1} \left(\frac{g}{a_c} \right) = \tan^{-1} \left(\frac{g}{\omega^2 r} \right)$$

Similarly, we can consider a cone rotating about a vertical axis (as shown in Fig. 6b) and can find the corresponding conditions under which quasi-static controllable flow can be achieved. In such a case effective angle of incline, α_{eff} , is given by

$$\alpha_{eff} = \tan^{-1} \left(\frac{g}{\omega^2 r} \right) + \alpha_c \quad (9)$$

where α_c is the included half angle of the cone, taken to be positive for a cone opening down and negative for a converging cone. Using the above definition for the effective angle of inclination, the criteria for controllable quasi-static flow is still given by equation (8). At any fixed position on a cone both of the terms in equation (9) determining α_{eff} are constant, however, as one moves down the cone the centrifugal acceleration term will change as the radius changes. We can use equation (9) to determine the shape of vertically rotating chamber that has a constant effective angle of inclination, α_{eff} . Such a cone will have a cone half-angle, α_c , that varies with, r , according to

Figure 6b

$$\alpha_c = \alpha_{eff} - \tan^{-1} \left(\frac{g}{\omega^2 r} \right) \quad (10)$$

Figure 7 shows representative shapes determined from equation (10) that could be used to form the upper part of a vertically oriented Cascade reactor.

The lower or converging portion of a vertically oriented Cascade chamber would necessarily need to rotate at a lower velocity than the upper portion. The most compact configuration would simply have the lower portion stationary in which case the convergence angle, α_c , for a constant effective angle of inclination, α_{eff} , becomes, by equation (10)

$$\alpha_c = \alpha_{eff} - \frac{\pi}{2}.$$

(Or, in other words, the cone surface could have a constant angle equal to α_{eff} measured from the horizontal). A realistic design of such a chamber would, of course, need to include a transition region wherein the rotating granular material spirals gradually to a circumferential velocity of zero as the angle of convergence changes to maintain quasi-static controllable flow. Figure 8 is a schematic showing a possible configuration for such a vertically oriented Cascade chamber. (The ability to maintain flow rate control from the downstream side of such a transition needs to be investigated).

MIXING, SIZE SEGREGATION AND DIVERGENT FLOWS

In addition to the concern of whether material will move or not, which has been the subject of the preceding pages, there is an additional concern of mixing and particle size segregation. As the flowing solids move through the chamber they will periodically (at a rate of 1 or 2 Hz) be hit with a high

Fig. 7. Representative shapes determined from equation 10 for the upper part of a vertically oriented Cascade reactor with quasi-static controllable flow of the Li_2O pebbles.

a — $\alpha_{eff} = 30^\circ$; $\omega^2 r_s = 2.3$

b — $\alpha_{eff} = 35^\circ$; $\omega^2 r_s = 2.9$

c — $\alpha_{eff} = 35^\circ$; $\omega^2 r_s = 1.9$

Fig. 8. Possible configuration for vertically oriented Cascade chamber with stationary lower portion.

intensity pulse of radiation. The neutrons in this pulse will penetrate well into the flowing layer and deposit energy as they are moderated and interact with the Li nuclei. The energy deposition from the neutrons will gradually heat the entire flowing bed, with somewhat higher heating occurring near the inner surface. The gamma rays will likewise penetrate well into the bed and cause heating over a significant depth. The x-rays, on the other hand, will be absorbed in a very shallow layer with a large part of their energy absorbed near the surfaces of the first layer of particles on the inside of the chamber. This will undoubtedly cause breakage (and vaporization) to occur and will leave an inner layer of broken particles at significantly higher temperatures than the remainder of the bed.

For optimum operation all particles would be heated equally. One way of approaching that optimum is to provide mixing of the flowing granular bed as it moves through the chamber. With the most important factor being the need to constantly replace the top surface layer that is absorbing the x-rays.

It is generally recognized (Hogg, et al. 1975) that the mixing of particulate solids can occur through two mechanisms:

- . turbulent, or macro-mixing, which involves the collective motion of large groups of particles.
- . diffusive, or micro-mixing, in which individual particles migrate by random motion through the surrounding particles.

Unlike fluids in which diffusion is a spontaneous process arising from thermal agitation, micro-mixing in granular solids only occurs when energy is supplied to the material, such as in shearing flow. Most mixing devices used in processing granular solids are concerned with providing macroscopic mixing

wherein significant quantities of material are forceably placed in another location in the flow (e.g., ribbon blenders, rotating drum mixers), in these processes, vibrational energy is also provided to the material and diffusional mixing also occurs, especially in those regions with high shear rates. Diffusional migration also exhibits itself in the percolation of smaller particles downward through shearing granular flows involving a wide size distribution of particles (in a gravitational field).

Controlled, quasi-static flow, on an incline plane, does not necessarily involve any significant shearing except near the entrance and exit. Thus, mixing of either macroscopic or microscopic nature is likely to be minimal in such flow. It is known however, that in inclined chute flows without downstream restrictions, steady state shearing flow can develop which exhibits substantial particle size segregation and diffusional mixing (see for example, Savage 1982, or Hogg 1975). Figures 9 and 10 show an example of large particles percolating to the top of a flowing layer in an inclined chute flow. Figure 9 shows a layer of (white) alumina particles flowing down an inclined chute. These alumina particles are slightly larger than the largest particles of oil shale that are deposited in a 1.0 cm thick layer over the top of them in Figure 10. After a few tens of particle diameters of travel down the chute the larger alumina particles are almost all on the top surface, while the smallest oil shale particles have simultaneously percolated to the bottom of the flowing layer. Such rapid diffusional migration is observed in this case because significant shearing is taking place and because significant

Fig. 9(a) Incline chute apparatus for demonstration of particle size segregation. Upper funnel dispenses Alumina (-4,+6 mesh) lower dispenses oil shale rubble (-6,+50 mesh)

Fig. 9 Large (-4, +6 mesh) Alumina particles on the bottom of inclined channel.

Fig. 10. An example of large particle: rising to the top in shearing flow on an inclined chute.

vibrational kinetic (thermal) energy exists in the flowing layer. If we wish to induce this same type of behavior in a flowing layer of Li_2O pellets in a Cascade chamber it will be necessary to insure that shearing flow occurs.

Fortunately, the designs under consideration for Cascade chambers all have divergent flow geometries that will force some shearing to occur. We do not know enough about the nature of diffusional motion in flowing granular solids to evaluate whether the shearing caused by the changing circumference of the chamber will provide sufficient diffusional mixing, however, flows involving alternate divergent and convergent flows are used in the mineral processing industry to obtain separation of heavy and light components in a slurry (see discussion of Reichert cones in Wills, 1982). Thus, we might well expect that the shearing action of the divergent flow would be sufficient for particle size segregation to occur.

If the divergence does not provide sufficient shearing to achieve rapid percolation of the hot fines through the bed, there are other measures that could be utilized to enhance such effects. It is known in powdered metallurgy work that flow around tight corners causes size segregation (Hawkins 1983a). This same phenomena could provide significant shearing in the bottom layers of a Cascade bed and also provide sufficient shearing through the thickness to cause percolation of the fines on the top surface into the flowing bed. Within the limits of the controllable quasi-static flow relation, equation 1, we have a range of angles, albeit somewhat limited, over which we can still maintain controlled flow. It may be possible to significantly increase the diffusional migration of particles by varying the shear rate so that, some

times, it is very rapid, and at other times quite slow as the material flows through a Cascade chamber. This could be accomplished by allowing the slope of the outer wall to vary periodically. That is, by making the outside wall a series of cascading steps whose amplitude and location would be designed to allow the shearing effect to affect the entire thickness of the flowing layer. Such steps could, for short distances, exceed the angle of repose restriction of equation (1), and, as long as the average slope did not exceed that restriction, the flow should still remain controllable at the outlet. Such a Cascade chamber might have a shape somewhat like that shown in Figure 11.

It should be noted that one potential advantage of a vertically oriented Cascade chamber is the very high shearing that would occur in the transition region from rotating to stationary parts of the chamber. This very rapid shearing would undoubtedly create sufficient size segregation to ensure that the hot fines percolate well into, if not entirely through, the flowing layer. However, as mentioned earlier, the ability to use downstream control of flow rate through such a shearing region needs to be investigated.

CORIOLIS FORCE EFFECTS

Since the anticipated flow velocities are small compared to the circumferential velocities, the coriolis forces will have only a small effect on the overall flow. It is, however, the coriolis force, transmitted from the wall and through the material, that causes the circumferential velocity of the particles to increase as they move "down" the incline to larger radii. Thus,

Fig. 11. Possible modification of Cascade chamber shape to include "steps" - thus increasing the shear rate periodically and increasing the percolation velocity of hot fines through the flowing layer.

SEVERAL ADJUSTABLE
STATIONARY PLOUGHS
REMOVE MATERIAL
FROM "FLAT" EXIT SHELF

CASCADE CHAMBER
WITH "STEPS"

EXIT PLOUGH DETAIL
PLOUGH LOCATION CONTROLS FLOW

INLET DETAIL
CHUTE WIDTH SETS MATERIAL DEPTH

coriolis effects will contribute to overall shearing deformations and consequently may affect percolation rates. It should be noted that overcoming the coriolis force (i.e. accelerating the mass) will require on the order of 150 h.p. in the drive motors for a 5 m diameter chamber, in addition to any power required to compensate for frictional losses.

DISCUSSION AND RECOMMENDATIONS

The ideas on shearing flow and diffusional motion of the particles discussed above are somewhat speculative at this point since we have little practice with divergent flows and most industrial experience has dealt with methods to eliminate size segregation not enhance it. Also, as mentioned at the beginning of this paper, the behavior of flowing granular materials is not very well understood. One of the major reasons for the current lack of complete understanding of granular flow behavior is the difficulty of obtaining experimental data on the details of the flow (e.g. the velocity field, the porosity distribution, the stress tensor interior to the flow, etc.) without disturbing the flow. Current theories often lack verification because of the difficulty of obtaining adequate data for complete verification. Recently, molecular dynamics like simulations (Walton 1982a, b; Campbell and Brennen, 1983) have started to provide insight into the details of shearing granular flows. A comprehensive program of sound experimental measurements combined with a discrete particle computer modeling effort could do much to advance the state of the science of granular flow, so that detailed engineering designs

would be possible. In order to better evaluate the feasibility of some of the design concepts put forth in this paper, this author would recommend that as many of the following studies as are practical be completed.

I. Experimental Study of Mixing/Segregation in Divergent and Non-Divergent Flows

Divergent flows similar to those occurring on the inside of an expanding rotating cone can be studied more readily in the laboratory by observing flows on the outside of vertically oriented stationary cone (or a section of a cone). Such a flow would have all of the features of a vertically oriented Cascade chamber except coriolis forces and could be made to simulate many of the features of horizontally oriented chambers. Of particular interest would be the rate of percolation of fines down through the material and how this is affected by the divergence. Diagnostic measurements similar to those of Savage and Lun (1982) and/or of Hogg et al., (1975) could be used to determine the vertical distribution of fines as a function of the distance traveled down the incline, except that quasi-static flow would be used instead of the rapidly shearing flow used in their experiments.

II. Experimental study of mixing/segregation enhancement caused by flow over steps in both non divergent and divergent flows

Within the overall limits of equation (1) the slope of the lower surface could be varied to cause periodic shearing (i.e. bending) of the flowing layer. The effectiveness of this induced shearing on enhancing percolation of fines could be examined by adding a corrugated bottom surface to the same test geometries studies in I above. These geometry modifications would be applicable to both horizontal and vertical orientations of Cascade beds.

III. Experimental examination of shear stress vs. shear rate in rapidly shearing granular materials

If a vertically oriented Cascade chamber is to be designed the shape of the transition region from rotating to stationary (and the ability to maintain controllable flow through that region) will depend significantly on the rate in which energy is dissipated and on the transmission of shear stresses through the shearing granular flow. A knowledge of such phenomena will also be extremely useful in designing the feed and exit portions of any Cascade chamber since significant shear is likely to occur in both of these areas. An understanding of shear stresses within a shearing material and the coupling from various wall conditions to the granular material would be extremely helpful in designing such features.

[It should be noted that a specialized experimental apparatus for studying shear stress vs. shear rate has recently been constructed at Bendix Corporation's Advanced Technology Center in Maryland. This equipment is not going to be used by the new corporation headed by Allied Chemical (now running the Bendix facilities). It may be possible to obtain this equipment at a fraction of the cost of building a comparable apparatus (D. Freitag, 1983).]

IV. Continued study of flow in rotating cones

The insight already gained by the limited tests conducted by J. Pitts speaks well for continued attention to the details of flow in realistic geometries. In particular, studies of various inlet and outlet design concepts are perhaps best performed on a rotating system. Inlet

configurations can be designed to maintain flow depth independent of flow rate and the outlet configuration can be designed so as to avoid the $\sqrt{g_{eff}}$ flow rate dependence typical of flows through orifices. This author in particular has several ideas for inlet and outlet designs that he would like to see tested on a laboratory scale before proposing them for a full scale Cascade chamber.

Also, tests of the transition region, from rotating to non-rotating, for vertical orientations could be performed if that configurations looks promising.

V. Discrete particle computer modeling of granular flow

A relative new research tool for granular material flow studies is computer modeling of discrete particle flow. This new tool allows us to examine the details of flow phenomena such as velocity profile, density gradients and internal stresses in the modeled materials. This ability to examine the details of the flow, for the first time, can allow for rapid development of the science of granular flow. Even qualitative observation of computer generated movie s of granular material flow have led to new insights in flow behavior and to the design of new processes involving granular flow (A. Lewis et al. 1983). This author feels that such computer modeling should be an integral part of interpreting the above experimental measurements. The insight provided by using a detailed discrete-particle flow calculation can be invaluable in uncovering difficult to explain results and the computer models may well be a very cost effective method of testing scale-up to full size

shearing flows. These computer studies, coupled with the experimental results, can lead to a thorough understanding of the phenomena involved. Armed with that understanding we can develop statistical mechanical and/or continuum description of shearing granular flow. We will then have advanced the science of granular flow enough to develop the tools necessary to scale designs from laboratory size to commercial size with some confidence.

Summary

Quasi-static controllable flow of Li_2O is obtainable in either horizontally or vertically oriented rotating chambers. In such flows the flow rate can be controlled at the exit point and the flow depth can be independently controlled at the entry point. The divergent nature of flows from small radii to large radii will necessarily cause shearing of the material to occur. This shearing may be sufficient to allow the natural size segregation in shearing flows to carry the hot fines on the inner surface down into and/or through the flowing particulate bed. Additional shearing can probably be induced in the flow to accentuate this effect, if necessary. Research into the nature of divergent quasi-static flow (and especially diffusive percolation of fines in such flow) will be necessary before we can be confident that such effects can be utilized in Cascade type reactors. Both discrete particle computer models and a set of physical tests have been recommended to obtain the data needed to evaluate proposed Cascade designs.

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