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# Layered Granule Chute Flow Near the Angle of Repose

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# LAYERED GRANULE CHUTE FLOW NEAR THE ANGLE OF REPOSE*

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Synopsis: A natural, two-layered gravity flow of sand can be obtained on chutes inclined at angles slightly above the angle of repose of the sand. The top-surface layer is free-flowing, is thin, and moves rapidly at supercritical velocity. The velocity depends mainly on the character of the sand and the chute inclination angle. The bottom layer is thick and moves more slowly, with the flow controlled by adjustable weirs at the chute exit. The velocity profile in the thick bottom layer is curved; as much as an order of magnitude higher velocity occurs in the upper portion of the layer than occurs along the bottom wall of the chute.

## INTRODUCTION AND APPLICATION

We conducted laboratory-scale experiments of sand flowing down a chute inclined slightly above the angle of repose of the sand. The sand entered the chute through an adjustable weir in the bottom of an inlet hopper. The flow at the exit of the chute was restricted, with sand flow permitted out of adjustable weirs, one near the free surface of the sand and one near the bottom wall of the chute. The flow of sand as it entered the chute was initially supercritical, but, within a few centimeters, the flow changed to a natural, two-layered structure with the free surface of the sand sloping slightly above the angle of repose.

In this natural, two-layered flow, a thin, top-surface layer moved at supercritical speed with considerable mixing. Sand in the top-surface layer was free-flowing. Its velocity depended mainly on the character of the sand and on the chute inclination angle and, indirectly, on the chute exit weirs. A thick, bottom layer moved more slowly, with the flow controlled directly by the chute exit weirs. We showed that the velocity profile in the thick, bottom layer was curved; as much as an order of magnitude higher velocity occurred in the upper portion of the layer than occurred along the bottom wall of the chute. Maximum velocity in the bottom layer was still substantially less than in the top-surface layer.

The granular flow we describe is complex. The flow includes material that is undergoing quasi-static deformation near the wall of the chute and material that is moving at supercritical velocity on the top surface. Existing analytic

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techniques and/or constitutive equations are not applicable over such a wide range of flow conditions. However, we are developing new numerical modeling techniques based on molecular dynamics principles [1,2] specifically for the calculation of granular flows. These numerical models calculate the motion of macroscopic granules as they interact with each other and dissipate energy through plastic deformation and frictional sliding. The work of Walton and Braun [2] is two-dimensional and involves a small number of granules. Extensions of their models to include large numbers of granules and inclined surfaces are under way. Completion of these extensions and some additional modifications to the boundary conditions will allow numerical simulation of the chute flows described here.

Our application for the experiments we report here involves the Cascade concept for an inertial-confinement-fusion reactor to produce electrical power (see Pitts [3,4] and Pitts and Walton [5]). Figure 1 shows the Cascade reactor, which includes a double-cone-shaped chamber rotating at 50 rpm with a moving, 1-m-thick, ceramic granular blanket held against the reactor wall by centrifugal action. The granules absorb energy from fusion reactions occurring in the center

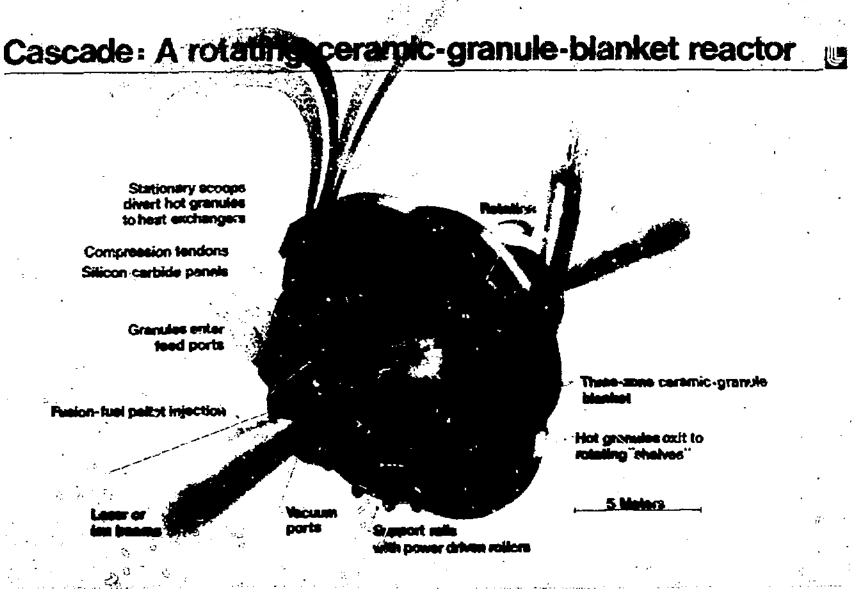


Fig. 1 Rendering of the Cascade conceptual reactor. 300 MJ fusion-fuel pellets are injected 5 times each second; the energy produced is converted to electricity with 50% efficiency.

of the chamber. The inner 100 mm of the blanket is composed of BeO granules; the outer 900 mm is composed of $LiAlO_2$ granules. All granules are approximately 1 mm in diameter--about the size of sand grains. Approximately one-third of the fusion energy is deposited at the inner surface of the blanket in the form of x rays and fusion-fuel-pellet debris. The remainder of the fusion energy is in the form of neutrons, which are absorbed in the balance of the blanket.

Neutron-energy absorption has an approximate exponential form (larger at the inner surface) in both the BeO and the $LiAlO_2$, but a step increase of about a factor of two occurs at the interface between the BeO and the $LiAlO_2$. Overall, an order-of-magnitude more neutron energy is deposited at the inner surface than at the outer surface.

We desire a radial velocity gradient in the blanket that matches the energy absorption in the BeO and $LiAlO_2$ regions, so that the exit temperature in the blanket is as spatially uniform as possible. This allows the highest average exit temperature and the highest potential efficiency for conversion of heat into electricity.

Our chute-flow experiments showed that we could obtain two-layered flow with a velocity profile approximating the energy absorption through the thickness of the Cascade blanket. We hope to be able to learn enough about control of the velocity profiles through future experiments and numerical simulations to obtain an even better match between velocity and energy absorption.

## EXPERIMENTAL APPARATUS AND RESULTS

Our apparatus is shown in Figure 2. It includes a 250-mm-wide clear plastic chute inclined at angles around $35^{\circ}$. Monterey-crystal amber-colored sand, Type 0, was used in the experiments. This sand has an angle of repose of about $34^{\circ}$ and a grain size of about 0.5 mm. However, we noted that the slope of the sand on the chute during experiments was closer to $32^{\circ}$, indicating that dynamic conditions may lower the effective angle of repose.

Our experiments were conducted by filling the upper container (positioned on a fork lift in Figure 2) with sand. The upper container was placed so that a pipe extending from the bottom of the container ended in an inlet hopper. The inlet hopper led to the entrance of the inclined chute. When a plate in the bottom of the upper container was opened, sand filled the inlet hopper to the elevation of the pipe exit. As sand moved out of a weir in the bottom of hopper and down the chute, replacement sand from the upper container automatically refilled the hopper.

Sand was prevented from flowing out of the chute until the start of a test by a removable plastic barrier positioned just upstream of the bottom end of the chute. When the plastic barrier was removed, sand flowed to the bottom end, out one or more of five exit weirs and into a second container (see Figure 3). The second container was located on a scale so that we could determine the flow rate. We adjusted the flow rate out of the various weirs by changing the angle of individual weir-exit plates. If an individual weir-exit plate was close to the horizontal plane, then no sand would flow out of that particular exit weir. We conducted tests with the middle three weirs closed (with flow only out of the top and bottom weirs). With the middle weirs closed, a thin, fast-moving, top-surface layer developed on the chute, and the material in this layer flowed over the top weir. The sand near the bottom wall of the chute flowed through the

Fig. 2  Test apparatus for the granule chute-flow experiments. The chute is made of clear plastic and its inclination angle is adjustable.

Fig. 3 Time exposure of two-layered sand flow on a chute inclined at 36.6°. Vertical markers are 2 cm apart; horizontal markers are 10 cm apart.

bottom weir. Depending on the adjustment of the top and bottom exit weirs, a portion of the sand flowing below the top-surface layer could be made to exit over the top weir as well. We did not normally close the bottom weir because this would establish a zone upstream where the sand was stationary. If stationary granules were present in the Cascade blanket, the granules would continue to heat until they melted, thereby destroying the granular nature of the blanket. In later tests, we used two exit containers and two scales so we could establish independent flow rates from the top and bottom weirs.
The sand was seeded with a small amount of white-colored alumina, which had a lower density and an average grain size larger than the sand (~ 3 mm). The alumina granules remained on the top-surface layer of sand as it flowed down the chute; thus, they acted as markers for motion pictures. We positioned flat mirrors at an angle so that when viewed from the side, the top surface, side surface, and bottom surface could be seen simultaneously (Figure 3) with a motion picture camera.

In these tests, data consisted of geometrical measurements to establish the chute inclination, sand flow rates, and motion pictures taken at 50 frames/s. By viewing the motion pictures frame by frame, we determined the velocity of the sand as a function of distance from the bottom wall of the chute. In some cases we took time-exposure photographs, an example of which is shown in Figure 3. In this figure, the chute is inclined at a 36.6$^{0}$ angle, and the bottom weir is closed to prevent motion in the bottom layer.

The sand entered the chute under the weir at the bottom of the inlet hopper. Sand at the upper right of the chute (shown in Figure 3) flowed down at supercritical speed. Because of the exposure time of the photograph, the sand is seen as a blur rather than as individual sand grains. In the center of the photograph, the flow changes abruptly, with only a thin layer of sand at the top flowing at supercritical speed down the chute and out over the top exit weir. The bottom sand layer is stationary, and individual sand grains can be seen. No flow was permitted out the bottom four exit weirs for this particular test. The central transition region is similar to a hydraulic jump with liquid flow. Note that the top mirror shows rapid supercritical flow over the entire width of the chute. The bottom mirror shows stationary sand separated from moving sand by a curved line. The line is curved because just upstream, the sand velocity in the center of the chute is larger than that at the sides of the chute.

When the bottom as well as the top exit weir was opened, the desired two-layered-flow was obtained. The region of stationary sand then moved at subcritical speed; the boundary between subcritical flow and supercritical flow seen on the bottom mirror moved upstream, and the curvature of the boundary was substantially reduced. The effects of the sides of the chute were still present but were smaller. Furthermore, the depth of sand was nearly uniform in the region where there was a thin supercritical top-surface layer flowing over a thick subcritical bottom layer; it did not increase to the lower left, as is shown in Figure 3.

The boundary between two-layered flow and complete supercritical flow moves even further upstream if the incline of the chute is reduced to a value closer to the sand's angle of repose. A small region of complete supercritical flow is always present just downstream of the weir in the bottom of the inlet hopper, but it is only a few centimeters long when the inclination angle is between 35 and 36$^{0}$.

Figure 4 shows the velocity profile when two-layered (supercritical/subcritical) flow exists on a chute inclined to 36$^{0}$. These data were obtained from motion pictures, taken at 50 frames/s, in which individual grains of sand on the side of the chute were followed from frame to frame. Total flow rate was measured by weighing the amount of sand flowing into a single exit container over a period of ~30 s and dividing the mass flow rate by the bulk density of the sand. The flow rate so measured was 940 $cm^3$/s, and the flow rate calculated by integrating the velocity profile was about 20% lower. The two values are in reasonable agreement and give confidence in the accuracy of both flow rate and velocity measurements. Further, the integrated flow rate is less, which is expected when side effects are considered.

Figure 5 shows similar results when the chute was inclined to 35$^{0}$ and where two exit containers were used to separately measure the flow though the exit weirs. Here the total measured flow rate was 1510 $cm^3$/s. Again, the flow rate determined by integrating the velocity profile was about 20% lower than the measured flow rate. The horizontal dashed line at a distance of 4.5 cm from the bottom is the approximate interface between sand that flowed over the top exit weir (60% of the total) and sand that flowed out of the bottom exit weir (40% of the total). In both of these tests (Figures 4 and 5), we see that the

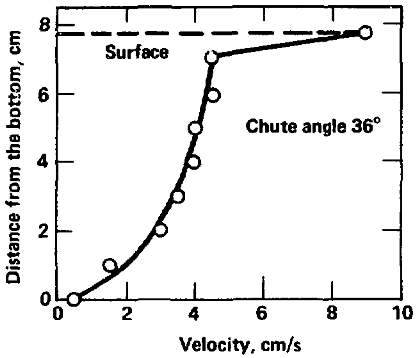


Fig. 4 Velocity profile of two-layered sand flow down a chute inclined at $36^0$. The entrance weir is 4 cm high. Flow rate, measured in a single exit container, was 940 $cm^3/s$.

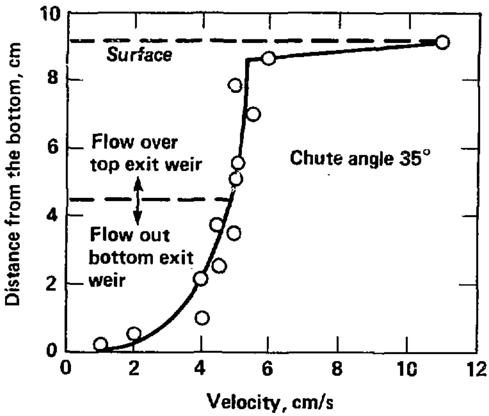


Fig. 5 Velocity profile of two-layered sand flow down a chute inclined at $35^0$. The entrance weir was 6 cm high. Flow rate, measured separately in two exit containers, was 1510 $cm^3/s$, with 60% of the flow passing over the top exit weir.

top-surface layer is moving approximately twice as fast as the material just a centimeter below the surface. The material near the bottom surface is moving quite slowly (an order of magnitude slower than the top surface layer) with the velocity increasing gradually with distance above the chute surface.

Through adjustment of the exit weirs, we were able to change the velocity profile in various ways. As already shown (Figure 3), a rapidly moving top-surface layer could be obtained even when the velocity in the lower portion of the granular layer was zero. Adjusting the flow out of the bottom weir affected the entire velocity profile. Adjustment of the top weir would either allow or prevent the rapid top surface layer from developing; however, the actual velocity of the top-surface layer seemed to be more a characteristic of the material and surface slope and be only indirectly controllable by adjusting the top weir.

While we still have much to learn about methods of tailoring the velocity profile on inclined chutes, these initial tests are quite encouraging. By judiciously choosing inclination angles and exit weir openings, we have obtained a range of velocity profiles.

## CONCLUSIONS

Experiments showed that two-layered granular flow can be obtained on a chute, inclined slightly above the angle of repose. The top-surface layer is thin and moves with high speed (supercritical flow). Velocity in the thin, top-surface layer depends mainly on the character of the granules and the inclination angle of the chute. The thick bottom layer moves more slowly, with the velocity controlled by the weirs at the exit of the chute. The velocity profile in the bottom layer can be varied by adjusting the top and bottom exit weirs.

The adjustable two-layered flow is advantageous for application to the Cascade inertial-confinement-fusion reactor because it permits the velocity profile to approximately match the energy-absorption profile in the granular blanket. This allows design of a thermally efficient blanket for conversion of fusion energy into electrical power.

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