OCT 05 1992 DOE/PC/90182--T7

Studies of Granular Flow Down An Inclined Chute

Quarterly Technical Progress Report

Year Two, Quarter Three: 13 June, 1992 to 12 September, 1992

Contract Number: DE-AC22-91PC90182

DOE/PC/90182--T7

Contract Duration: 12/13/90 to 12/12/94

DE93 004936

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

Progress Report:

An experimental apparatus has been constructed in order to study the flow of granular material down an inclined plane. A preliminary series of experiments were run in order to examine the effects sidewalls have on the steady-state mass flow rate of granular material in a rectangular, inclined chute. Initial studies also indicate a variety of regimes of flow behavior are possible. This manuscript provides a description of the apparatus and summarizes the findings of these nascent studies.

Experimental Apparatus

The flow region of the experimental apparatus consists of a rectangular aluminum chute with clear lexan sidewalls. The interior of the chute is four meters long, 46 cm tall, and the width is adjustable from zero to 25 cm in 2.5 cm increments. A drawing of the chute cross section appears in Figure 1. The 19 mm channel design of the chute base was designed to deflect less than .25 mm for the entire chute when supported horizontally by its ends. The base of the chute is designed to be covered with interchangeable inserts, allowing different base roughness conditions to be studied.

The angular range which the chute is to be operable in was specified as 0° to 35° . Additionally, the chute had to be adjustable to within the 0.25 mm tolerance at any angle. In order to achieve this, the chute is supported at six points and pivots at the top (entrance) in a single plane, as shown in Figure 2. The lower four supports consist of square telescoping tubing to allow for the various angles. At the base of each of these adjustable legs is a worm gear screwjack. One complete turn of the shaft on these jacks extends the leg

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0.635 mm. At the two top pivot points there are adjustable wedge jacks. These six jacks (one for each support point) allow the chute to have the micro-adjustability required. There are ten pivot points, each physically achieved by a pillow block bearing.

The driving force for the granular flow in the experimental region is gravity. The vehicle which re-circulates this flow is an 46 cm Corra-Trough belt conveyor manufactured by Buck-El, Inc. A drawing of this conveyor is shown in Figure 3. Entrance and exit chambers were designed to route the flow between the chute and the conveyor. Both devices had to be flexible because the position of the chute relative to the conveyor changes each time the angle of the chute is changed. Photos of the entrance and exit chambers appear in Figures 4 and 5, respectively. A 15 cm iris valve controls the main flow between the top hopper and the entrance chamber.

Finally, to control the entering flow more accurately, an adjustable gate apparatus was constructed. This mechanism, shown in Figure 6 positioned at the top of the chute, is adjustable for any width and can be positioned anywhere along the length of the chute. The aluminum plate which forms the gate itself is what allows the adjustability as it is completely interchangeable, permitting an almost infinite number of entrance conditions to be created.

The first step in setting up the chute is angle adjustment. The chute is supported by a movable hoist and the pins are removed from the four telescopic leg supports. Pivoting about the two top support points, the chute is lowered to the proper angle. The angle is read by an Inogon inclinometer, which uses a vernier scale and two diffraction grating discs and is accurate to 0.2° . The pins are replaced and the hoist removed when the angle is close to the desired inclination. A somewhat iterative process is performed whereby an angle reading is taken at different points on the chute base and the six legs of the chute are adjusted until the angle is the same at all points.

The granular material used in the experiments described in this report are technical quality glass spheres, three millimeters in diameter. These beads are produced by Cataphote, Inc. Cataphote lists the tolerances for the 3mm spheres at ± 0.2 mm. The average mass of a single bead was measured to be 0.034 g which gives an average measured specific gravity of the glass at 2.42 g/cm^3 .

Chute Width Effects

A preliminary series of experiments were run in order to examine the effects sidewalls have on the steady-state mass flow rate of granular material in a rectangular, inclined chute. Presumably, the friction between the sidewalls and the flowing material will slow the flow rate of that material. The relative effect of the sidewalls should decrease with increasing width for a given flow entrance condition. For instance, when the width of the chute is at a minimum (one grain diameter), the sidewalls will have a maximum frictional effect. And as the width approaches infinity, the sidewalls will have a minimum frictional effect. It is desired to know at what chute widths the sidewall effects will reasonably approach this minimum, if this condition can even be approached with the existing apparatus. The relationship between chute width and flow rate will be important to know during more involved experiments which will follow this initial investigation. These experiments will include the

measurement of localized grain density, local velocity and individual grain dynamics and collisions.

To vary the chute width, Plexiglass inserts were accurately for four different widths: 10, 15, 20, and 25 cm. To set the width, the chute's removable wall is loosened to allow the base inserts to fit between the walls. Next, the sliding wall is pressed against the inserts and the bolts tightened. The entrance chamber opening is then lined up with the centerline of the chute.

The gate of Figure 6 is positioned approximately 20 cm from the top of the chute. This gate, when opened, provides a rectangular section through which the granular material enters. The area of this section is simply the width times the height of the gate, $A = w \cdot h$. In order to provide consistent entrance conditions for each experiment, enough material must be in the system such that just upstream of the entrance gate the glass beads are stagnant, forming a reservoir analogous to "head" in a fluid flow situation.

Figure 7 is a picture of the head formed when the gate is closed and the iris valve opened. In this way, material begins with effectively zero velocity and accelerates only as it passes through the rectangular entrance section. The height of the entrance gate is set with the help of an aluminum gage milled from .635 cm 3.81 cm in .635 cm increments. Thus there are four different widths and six different entrance heights which can define a single run of the chute system.

The rate of mass discharge was mechanically measured by a beam-balance linked to a timer, as shown in Figure 8. This method produces a time-averaged mass flow rate which is acceptable for the present experiments since the flow is essentially steady-state.

To take a measurement, the first step (after setting the height and width) is to turn on the conveyor and open the iris valve. The timer is reset, a catch bucket is placed on the balance and the counter weight is set to a mass, m_1 , high enough to offset the weight of the bucket. Next, the flow is diverted from the bottom hopper of the conveyor into the catch bucket. As the mass in the bucket surpasses m_1 the arm of the balance trips a switch which starts the timer. Now, enough additional weight, m_2 (≈ 15 kg for small h and 40 kg for large h), is added to the counter balance arm. When the mass in the bucket reaches m_2 the switch is tripped again and the timer stopped. If t is denoted as the time that appears on the timer, then the mass flow rate is given by $(m_2 - m_1)/t$.

For this set of experiments, studies were conducted with 4 chute widths, 4 to 6 gate heights, and two angles of inclination. The base consisted of smooth aluminum. At both angles (12.6 degrees and 16.0 degrees) the flow was not fully developed; rather it was accelerating. The results, in terms of mass flow rates, are shown in Figure 9. As expected, the mass flow rate increases as either the gate height or chute width is increased. The effect of chute width is examined by presenting the mass flow rate normalized by the chute width, as a function of width, as shown in Figure 10. The width normalized mass flow rates exhibit very weak dependence upon chute width.

Flow Regimes

By varying the inclination, gate height, or base roughness characteristics, a variety of flow regimes may be obtained. This is consistent with previous literature on granular flow down inclined chutes. For example, the flow may be quite dense, with presumably both friction and collisions mechanisms for momentum transfer. An example of this is shown in Figure 11. Unfortunately, the reproduction quality is somewhat poor; each bright spot represents a glass sphere. Near the base of the flow, spheres are tightly packed and aligned in rows, but higher in the flow the concentration is lower and the packing is more random. At the free surface, there are some undulations observed. An example of a less dense, more collisional flow is shown in Figure 12. In this flow there is no evidence of layered structure, and the concentration near the free surface is quite dilute. Presumably collisions between grains are the dominant mechanism for momentum transport in the flow.

Transitions between flow types are observed. Figure 13 illustrates a transition from a thin, rapid flow to a thick, slow flow. The transition is reminiscent of a hydraulic jump. The jump is achieved by partially restricting the discharge at the bottom of the chute. By varying the restriction, the jump can easily be made to migrate in either direction.

Discussion

The dynamics of the flow, with the same material at a fixed angle of inclination, are strongly influenced by the entrance conditions, the exit conditions, and the base characteristics. A systematic study of these effects is required. The effects of the side walls upon the rate of mass discharge is small, although the grain velocities near the side wall certainly are influenced to a greater degree.

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Acknowledgements

This work was supported by the U.S. Department of Energy as a part of the Granular Flow Advanced Research Objective (GFARO).

Figure 1. Dimensions of experimental chute.

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Figure 2: Drawing of Chute

Figure 4. Entrance chamber.

Figure 5. Exit chamber.

Figure . 6. Photograph of entrance gate apparatus affixed to top of chute.

Figure 7: Photograph of "head" which forms behind the closed entrance gate.

Figure 8: Beam balance and timer used to measure mass flow rate.

Figure 9: Mass flow rate as a function of gate height and chute width for two angles of inclination.

Figure 10: Mass flow rate normalized by chute width, as a function of gate height and chute width for two angles of inclination.

Figure 11: Image through the side wall of relatively slow, dense, flow.

Figure 12: Image through the side wall of relatively fast, sparse, flow.

Figure 13: Image through the side wall of an abrupt flow transition.

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