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The mixing of powders flowing down an inclined plane

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An apparatus has been constructed in which a pair of hoppers feed powders at controlled rates to the top end of a chute in two moving layers, one on top of the other. The layers move down the chute and at the lower end are separated again by an adjustable knife edge. Subsequent analysis of the fractions obtained enables the amount of mixing which has occurred to be determined. Since the mixing takes place under controlled conditions through a known area of contact between the powders, the apparatus measures "powder miscibility". Two photoelectric cells enabled the powder velocity to be measured. Powder velocities and bed structure are reported for the flow of single layers of sand of various thicknesses. Mixing results are presented, in terms of an effective diffusion coefficient, for the flow of 30/36 mesh sand.

THE rate of flow of particulate material through orifices of various shapes and sizes at the base of hoppers has been studied by a number of workers e.g. Brown & Richards (1965) and Pilpel (1966), who have demonstrated that the rate of outflow is independent of the head of powder above the orifice. Such conclusions apply to powder in free fall after passing through the discharge orifice. Although studies have been reported on the flow of powder along inclined chutes, (Harris, 1963) the chutes used had a porous base, being fed with compressed air so that the powder was fluidized and lifted clear of the base. Material was thus enabled to flow along the chute at quite small angles of tilt. Little work has been reported on the gravity-induced flow of powders down inclined planes, although it is a common phenomenon in equipment handling industrial solids. The flow of particulate material down an inclined plane also takes place in rotary drum mixers, in rotary coating pans and in ball mills where the sloping face of the charge in the rotating drum is made up of particles moving down in a combination of rolling and sliding.

Work described below with an inclined chute was aimed at simulating such a sloping face of tumbling particles. Parameters investigated include the angle of the face, the rate of feeding the powder which controls the depth of the layer, the effect of feeding one layer on top of another which gives a measure of the amount of mixing, and finally the roughness of the chute which gives some degree of control of the amount of shear imposed on the particles.

Experimental

The apparatus, shown diagrammatically in Fig. 1, consists of a pair of hoppers which feed two streams of powder, one on top of the other, to the upper end of an inclined polished brass chute, 6·3 cm wide, 50 cm long, with sides 1·5 cm high. The two layers of powder slide or roll down the chute, and at its lower end are separated again by a horizontal knife edge,

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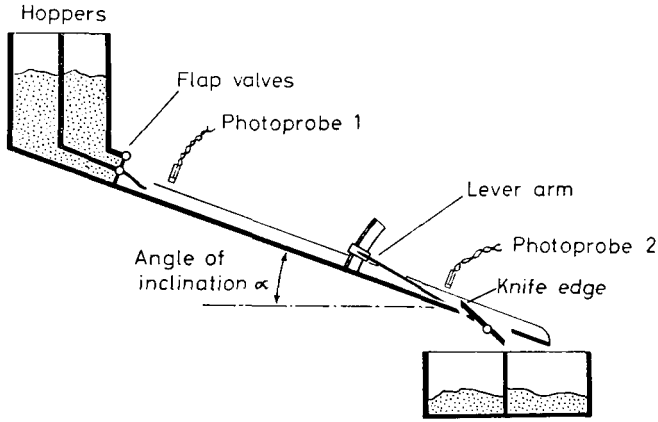

FIG. 1. Diagram of the apparatus. The hoppers feed sand through the (preset) openings of the flap valves onto the chute, set at the required angle α. The knife, adjusted by the lever arm, splits the bed at the lower end of the chute. The photocells measure the time which the material takes to pass from one to the other.

each layer going into a separate container. Any mixing which has taken place between the two layers is assessed by analysing the contents of the two containers.

The powder outflow from each hopper is controlled by a flap valve, operated by a long lever so that it can be opened rapidly. An adjustable stop enables the degree of opening to be set in advance so that the outflow rate is predetermined. The normal requirement is that the flowrates from the two hoppers shall be identical. The hoppers and the chute are integral with one another, so that the chute angle may be adjusted without effect on the hopper delivery. A contoured plate leads the powder smoothly from the upper hopper into the upper layer. Without this plate, the upper powder stream seriously affects the lower.

After falling down the chute, the layers are separated by an adjustable knife edge, the lower layer going beneath the knife into one Perspex box, whilst the upper layer goes over the knife into another. Preliminary trials are required at any given chute angle to ensure that equal amounts of powder are delivered in equal times from the hoppers, and that the knife edge splits the travelling bed in half so that equal amounts are collected, during a run, in each sample box.

The apparatus exposes a known interfacial area of one powder to another, under controlled and reproducible conditions of flow and shear. The amount of diffusional mixing taking place across this plane area is determined by analysis of the collected samples: it is a procedure analogous to the classical method of measuring the diffusion coefficient of a solute in a liquid. The mathematical relation between diffusional transport thus determined and the diffusion coefficient of the solute (Stefan-Kawalki data) has been conveniently tabulated by Jost (1960).

For the measurement of powder velocity, two small probes were constructed, each containing a Mullard ORP 11 photoconductive cell. Using a double-beam storage oscilloscope in the externally-triggered,

single-sweep storage mode, it was possible to record a voltage change from each probe as the powder bed passed it, together with a measurement of the elapsed time interval. A typical trace is shown in Fig. 2. The velocity was also checked by taking photographs of the moving sand bed at exposures of 1/100 and 1/500 sec. The lengths of the streaks formed by individual particles could be measured with sufficient precision to confirm not only that the photoelectric method was yielding correct results but also that particle velocities much greater or much less than the mean bed velocity did not occur.

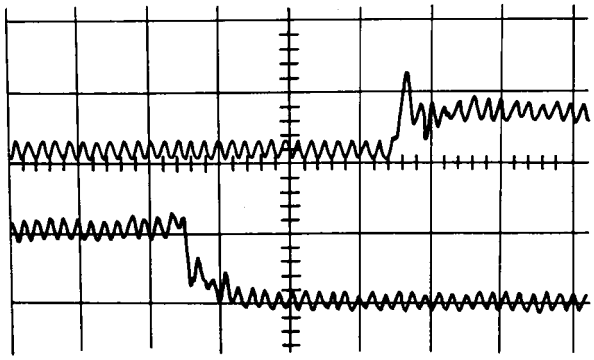

FIG. 2. A typical pair of traces obtained from the photoprobes. In the horizontal direction 1 division = 50 m sec, and in the vertical direction 1 division = 5 V.

To determine the bed thickness, two methods were used. For the first, the small knife-edged plate at the lower end of the chute was used. This plate pivots on an axle and may be tilted by moving an arm at the side of the chute. When in the retracted position, the plate fits neatly into the chute and particles pass undisturbed over it. As it is raised, it splits the descending bed, some particles passing below it and some above. Thus it was possible to determine the weight of particles in the bed travelling at any height above the chute surface.

For the second method, a knife edge was lowered onto the flowing bed by means of a micrometer screw and the position was noted at which the edge caused particles to accumulate on its upstream side. This was determined with a reproducibility of 0·05 mm.

The material used to form the flowing beds was Leighton Buzzard sand (George Garside Ltd.) which has uniform properties and rounded grains. The fraction used was that between 30 and 36 mesh, a size range of 422 to 500 μ. Where colour was important, as in the mixing experiments, it was dyed green with Naphthol Green B. This had no effect on the flow properties, but analysis by a light reflection method was rendered easy and rapid.

Mixing determinations were made as follows. Each hopper was loaded with 300 g of sand. The flap valves were opened simultaneously, and the sand flowed as two layers down the chute, the upper layer being directed smoothly onto the lower layer by the fairing installed for this

purpose. The particle velocity was measured by the two photoprobes and the layers were split by the knife edge and directed into twin Perspex collecting boxes. The two collected fractions were separately homogenized by shaking and stirring before being analysed by means of a photosensitive transformer ratio-arm bridge, (Deer, Ridgway & Rupp, 1968). The bridge measured the amount of light reflected by the mixed sand by comparing it with unmixed sand, either white or green. Analysis was rapid, taking about 30 sec per sample, and accurate to better than 0·5%.

The chief difficulties encountered were in the setting-up. Preliminary runs with mono-coloured sand samples were necessary to ensure firstly that the two hoppers emptied in exactly the same time, so that both layers ceased flowing together, and secondly to ensure that the adjustable knife edge was correctly positioned to direct an equal quantity of sand into each collecting box. These adjustments became easier as operating experience was accumulated. The adjustment of the hopper flap valves was the more important, since if one layer flowed for a shorter time than the other, the last of the sand, whether from the upper or the lower hopper, would flow as a layer of half the normal thickness and would all pass beneath the knife edge, falsifying the results. Failure of the knife edge to split the bed into two 300 g portions was less serious, because the error thus introduced is second-order.

Results and discussion

FLOW OF A SINGLE LAYER

As a preliminary experiment, the time taken for the front of the sand bed to travel a distance of 35 cm was determined as a function of chute angle, measured from the horizontal, and as a function of flap valve opening, using the lower hopper opening only. The upper photoprobe was positioned as close as possible to the flap valve, and the lower was 35 cm from it. The results are shown in Fig. 3. As would be expected, increasing the slope of the chute decreases the time of travel. There is also a tendency for the sand velocity to increase with increasing valve opening, i.e. increasing layer thickness.

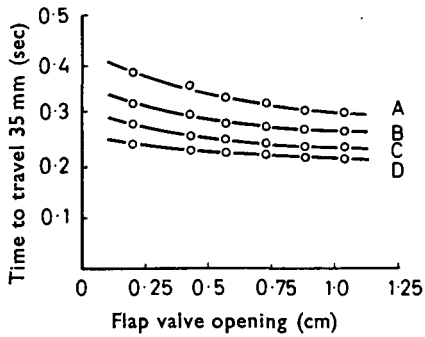

FIG. 3. Time to travel a distance of 35 cm down the chute, as a function of flap valve opening. The letters on the curves refer to the chute angles. A = 60°, B = 50°, C = 40° and D = 32·5°.

TABLE 1. BED VELOCITIES AS MEASURED BY THE PHOTOPROBES

Angle of chute degrees	Time (sec) to traverse a distance of			
	15 cm	25 cm	35 cm	45 cm
24·5	0·181	0·285	0·383	0·475
32·5	0·156	0·244	0·338	0·390
37·5	0·143	0·222	0·288	0·360
40	0·142	0·211	0·281	0·340
45	0·133	0·205	0·261	0·320
50	0·126	0·194	0·251	0·306
61	0·117	0·176	0·229	0·271

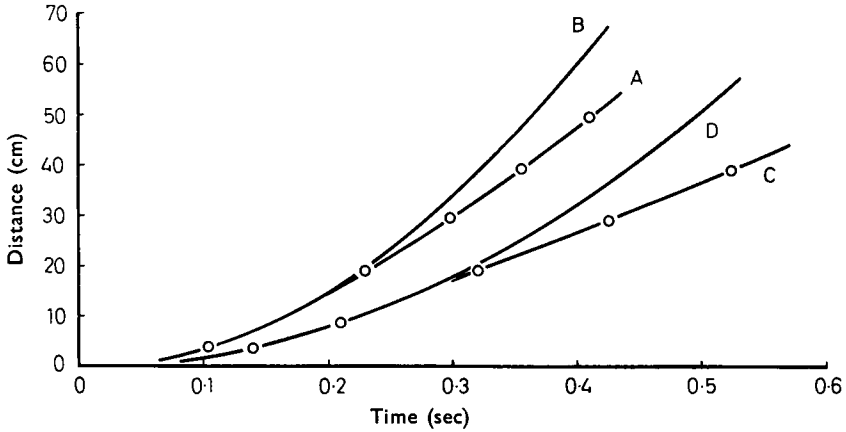

FIG. 4. Distance versus time plots, from the data of Table 1 (Zero shifted by 4 cm). The ideal curves are of the form distance $= \frac{1}{2} g \sin \alpha$ (time)^2. Curve A is for a chute angle of 50°, and curve B is the corresponding ideal curve. Curve C is for a chute angle of 24·5°, and curve D is the corresponding ideal curve.

The main body of the experimental data for flow of a single layer are given in Table 1, where the time intervals are listed for travel over distances of 15, 25, 35 and 45 cm between photoprobes, for various slopes of the chute. In each case the upper probe was 2·8 cm from the flap valve. Fig. 4 shows two distance-time plots derived from the data of Table 1. Also shown are the "ideal" curves which would be obtained for frictionless powder sliding down an inclined plane at the particular angle. These are easily calculated, since the acceleration is $g \sin \alpha$ where g is the acceleration due to gravity and α is the angle of inclination. In Table 1, zero time is the instant at which the powder passes the first photoprobe (2·8 cm from the flap valve). Initial agreement with the first part of the ideal curves in all cases is best when the time zero is taken to be 4 cm before the first photoprobe, i.e. 1·2 cm inside the hopper. This is effectively the point at which the powder starts from rest. The experimental curves, with this zero correction, follow the ideal curve but then fall below it as frictional forces come into play. It would seem reasonable that a constant, terminal velocity would be attained eventually in all cases if the chute were long enough. At an inclination of 24·5° constant velocity is practically

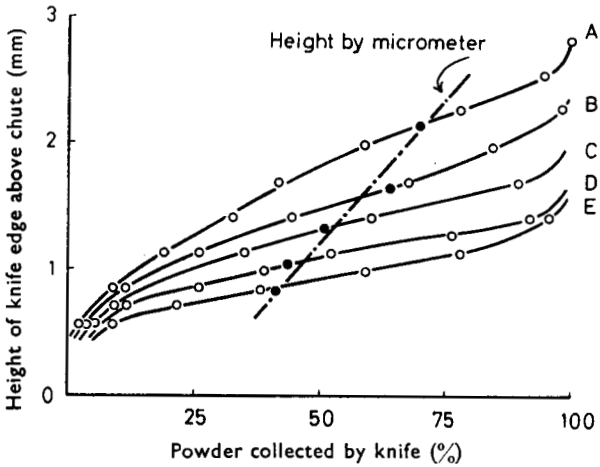

FIG. 5. Percentage of the flowing layer caught by the knife as a function of height of the knife edge above the chute surface, at a chute angle of 32·5°. The letters on the curves refer to the flap valve opening: A = 3·4 mm, B = 5·0 mm, C = 6·5 mm, D = 8·0 mm, E = 9·6 mm.

achieved, but at greater angles than this the sand is still accelerating even at 47·8 cm from the flap valve.

Fig. 5 gives the results of measurements of the percentage of the flowing layer diverted by raising the adjustable knife edge to various heights above the surface of the chute. The flowrate increases by a factor of more than ten between the lower and the upper curve, whereas the ordinate, the layer thickness, is only doubled.

If the velocity of all particles in the bed is approximately the same, and equal to the velocity measured by the photoprobes, then the density variation through the depth of the flowing layer may be calculated. This is done by finding the increase in weight of collected powder for each increase of height of the knife edge. Since the chute width is known, the area of cross-section through which a known weight of sand passes, at a known velocity, is also known. The density may be calculated from the simple relation—

$$\text{mass flow-rate} = \text{density} \times \text{linear velocity} \times \text{area perpendicular to flow direction}$$

Density profiles through layers of various thicknesses are shown in Fig. 6. In all cases there is a layer of low density, or high voidage, near the chute surface. This is to be expected, as any drag force applied to the bed will increase its voidage.

In the thinner beds, where the bed depth approaches one particle diameter, the drag produces rolling of the particles, and probably some saltation occurs too, so that some particles leap over the knife edge. In the thicker beds this type of motion will be prevented by the upper layers of the bed: shear will occur and voidage will increase.

The density increases throughout most of the depth of any bed, and the

maximum density achieved increases with overall bed thickness. The maxima of the density curves themselves lie along a curve which is tending asymptotically to a value of almost 1·3 g/ml as thickness increases. This may be compared with the bulk density of the stationary sand, which is 1·6 g/ml.

It should be stressed that the density profiles as drawn are based upon the assumption that the linear velocity is constant throughout the depth of the bed. This is an approximation; to determine the velocity within the bed would require more sophisticated techniques than have been used in the present work. If the opposite assumption, constant density through the bed, were adopted, the curves of Fig. 6 would be velocity profiles. This assumption, however is less likely to be correct.

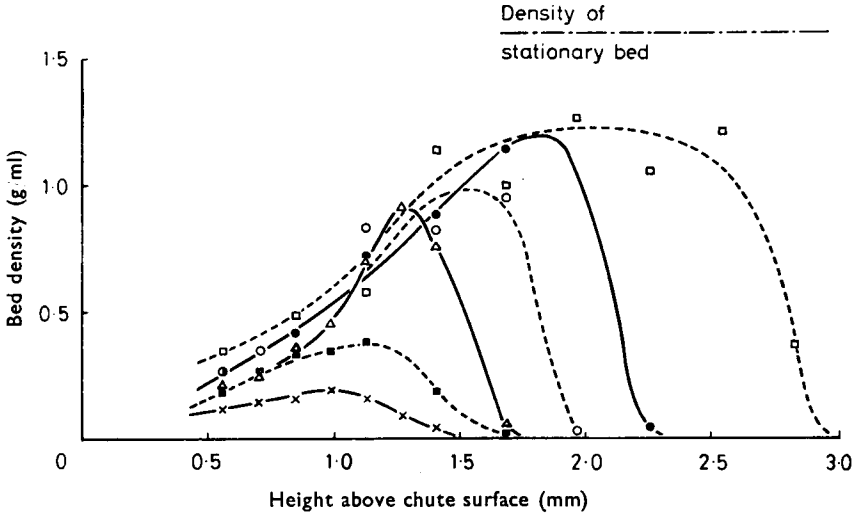

FIG. 6. Profiles of density at any particular level in the bed as a function of distance from the surface of the chute. Flap valve openings ×, 2·0 mm. ■, 3·4 mm. △, 5·0 mm. ○, 6·5 mm. ●, 8·0 mm. □, 9·6 mm.

THE MIXING OF TWO LAYERS OF FLOWING PARTICLES

Runs were made in groups, each group being characterized by flap valve opening. Having set the valves, the chute angle could be changed without further adjustment being needed. Two runs were made at each chute angle, one with green sand as the upper layer and one with white, in case any difference in flow properties had been caused by the dyeing process. The efflux time of the sand from both hoppers was noted. The results are presented in Table 2. There was no regular trend according to which colour of sand formed the upper layer of the flowing bed, and the percentages given in the Table are each the mean of at least two measurements, one with each colour on top. From the observed compositions of the two layers separated by the knife edge, the value of the quantity $h/2\sqrt{Dt}$ may be found from the Stefan-Kawalki tables (Jost, 1960).

TABLE 2. MIXING RESULTS FOR SUPERPOSED FLOWING LAYERS OF GREEN AND WHITE SAND

Chute angle degrees	Time of contact (sec)	Depth of lower layer (cm)	Green sand %		Diffusion coefficient cm^2/sec
			Upper layer	Lower layer	
32·5	0·342	0·217	87	13	0·303
32·5	0·342	0·157	78·9	21·1	0·391
32·5	0·342	0·110	80·7	19·3	0·165
32·5	0·342	0·079	73·4	26·6	0·0163
32·5	0·345	0·059	60·8	39·2	0·0219
32·5	0·348	0·048	49·4	50·6	0·0467
40	0·295	0·217	87·6	12·4	0·338
40	0·295	0·157	75·1	24·9	0·652
40	0·295	0·110	80·6	19·4	0·199
40	0·295	0·079	71·3	28·7	0·0219
40	0·297	0·059	54·4	45·6	0·0425
40	0·299	0·048	49·2	50·8	0·0488
50	0·256	0·217	88·8	11·2	0·309
50	0·256	0·157	77·8	22·2	0·588
50	0·256	0·110	82·2	17·8	0·246
50	0·256	0·079	67·6	32·4	0·0327
50	0·257	0·59	56·7	43·3	0·040
50	0·258	0·48	49·3	50·7	0·0591

D is the diffusion coefficient, t the time and h the thickness of each layer. The time of contact is obtained from the photoprobe measurements, and the setting height of the knife edge necessary to collect half the bed is known. This gives h for the lower layer, and it is assumed to have a similar value for the upper layer. Thus D may be calculated.

Variation of diffusion coefficient with increasing layer thickness, i.e. with increasing rates of powder flow, is shown in Fig. 7. The curves all start from a low value, increase to a maximum and then decline. The low values occur at small bed heights, where visual observation shows that the voidage is high and the particles in the upper layer have ample opportunity to fall through into the lower layer. The Stefan-Kawalki tables provide the minimum uniform value of D necessary to achieve the observed amount of mixing, and at small bed thicknesses this is a small value.

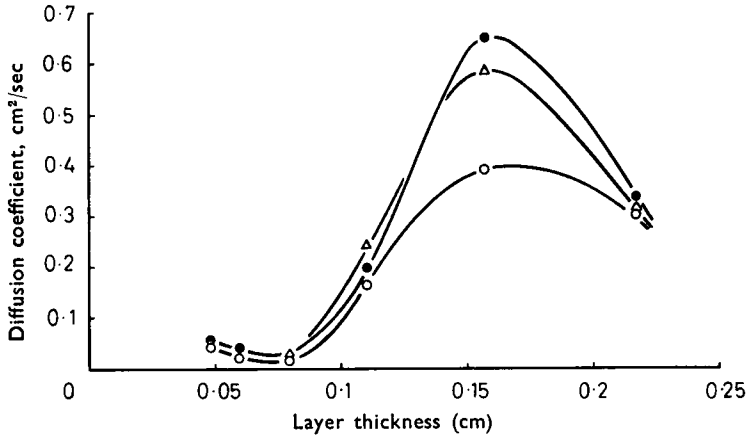

FIG. 7. Diffusion coefficient as a function of half-depth of the flowing layer, and hence of the rate of flow. ○, 32·5°. ●, 40°. △, 50°.

The possibility of a higher value at one part of the flow path and a lower value elsewhere is not excluded. As the layer thickness increases, the amount of diffusive mixing increases (although the percentage composition change actually achieved decreases). This is presumably due to the increasing amount of shear between the upper and lower layers.

At still greater layer thicknesses the increase in density causes the bed to become more resistant to shear as the amount of void space becomes smaller (Fig. 6). Under these conditions the bed is sliding as a whole and tending to act as a rigid body. Hence the value of D decreases.

Further development of the apparatus is possible. For example, it would be advantageous to increase the chute length to allow different contact times to be studied at the same angle. At present, contact time can only be changed by changing the angle of the chute. However, it has been shown that the miscibility of granular powders can be examined by the method described, and that the technique has potential usefulness in development work. In this connection it could be used to assess the size segregation of powders in movement.

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