Gravity discharge of powders at high flux densities through the exploitation of intensified gas induction effects

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Summary Many industrial processes involve the discharge of powders or granular material. Examples of this include the filling of road/rail wagons at the larger end of the scale of activity, and filling of big bags or sacks on a smaller scale. For the majority of these applications it is desirable to achieve a degree of consistency and repeatability in what flow stream property of successive discharges for the in flight material in order to facilitate process control and accuracy of filling. Most processes utilise a combination of aeration and/or large outlet sizes to obtain high instantaneous discharge rates – often to the detriment of accuracy or control.

This paper will consider the fundamentals of a previously unreported discharge behaviour that is specifically linked to the gravity discharge of plane-flow (wedge) type vessels when interfaced to a secondary plane-flow geometry.

1. INTRODUCTION

A previous paper presented at ICBMH 2001 [1] by The Wolfson Centre for Bulk Solids Handling Technology highlighted a programme of work investigating discharge irregularities at a coal loading terminal in the UK. Within the programme of work a set of data was generated that indicated a repeatable discharge phenomenon occurred over a small range of outlet sizes that resulted in a boosted discharge rate before returning to more conventional behaviour at aperture sizes either side of the affected range. No explanation for this behaviour was formulated at the time.

Subsequent research undertaken by the author[2], whilst investigating discharge behaviour of detergent base powders using a modified version of the same test rig used with the coal project, demonstrated the same discharge phenomenon. This led to an in-depth investigation into the phenomenon which in turn led to the delivery of a theory for the cause of the discharge instabilities. The potential for commercial exploitation through the intentional manipulation of the factors responsible for the boosted discharge behaviour has been recognised; and the techniques necessary to intentionally invoke the flow behaviour for process advantage have been made the subject of two international patents now held by The University of Greenwich, London, UK [3].

2. TEST PROGRAMMES

Previous trials on the discharge of sub 5mm coal blends through a 1/12th scale test rig which was constructed to simulate one "leg" of a twin outlet mass flow silo had shown that a discharge instability could be generated over a very limited range of outlet size. The specific geometry leading to the outlet is shown in fig 1.

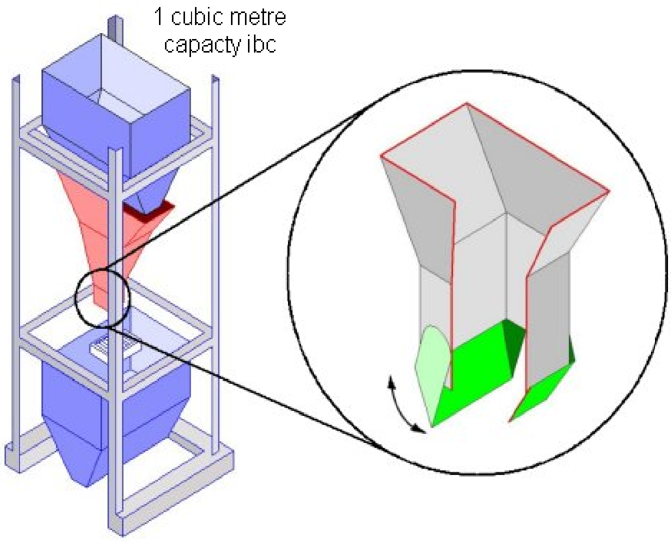

Fig 1   Diagram illustrating outlet geometry associated with the coal discharge test rig

The aperture size for this test rig was defined by the adjustment of a paired set of externally convergent doors. The positioning of the doors effectively adjusted the outlet area by the widening of the slot proportions defined by the leading edges of the doors. Fig 2 demonstrates the boosted flow associated with the flow instability.

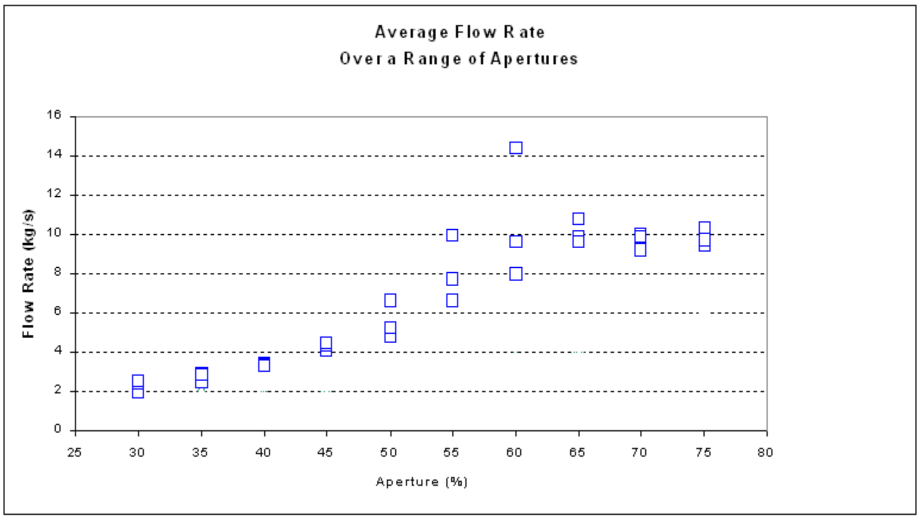

Fig 2   Graph showing the flow rate obtained over a range of aperture sizes

From the graph it can be seen that flow rates appear to increase as apertures reduce from 80% to 65% at which point the discharge rate increases prior to decreasing towards 30% in the manner expected (of a cross sectional area related variable). This change in flow behaviour could be detected for coal prepared to a range of size distributions (nominally fine rich, medium and fines deficient – all within a sub-5mm particle range).

A subsequent programme of research work used a modified form of the test rig to investigate the discharge behaviour of a detergent base powder. Despite a fundamental difference in the configuration of the outlet during operation the same flow anomaly was observed (see Fig 3).

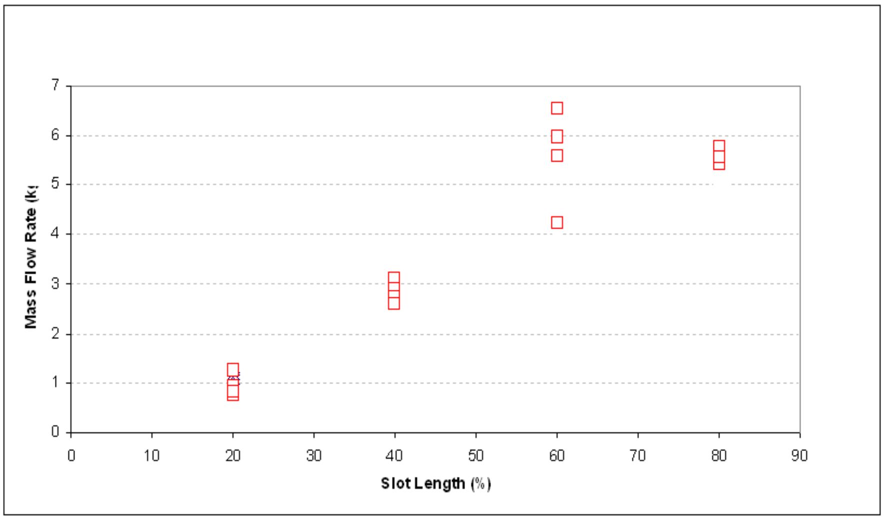

Fig 3 Graph showing the flow rate obtained over a range of aperture sizes

Investigation of the likely cause of this discharge behaviour initially focused on the geometry used for the outlet/flow control for the two test rig configurations. Fig 4 illustrates that the main feature in common for both configurations was that the outlet was generally rectangular in aspect – however, during turn down of the flow rate it could be seen that system 1 (coal) altered the outlet area by increasing the width of the outlet, whilst keeping the length constant – i.e. transitioning from a long narrow slot to a much wider aspect ratio. By contrast system 2 (detergent) affected a change in outlet area by maintaining a constant outlet width but allied to changes in length (see Fig 4).

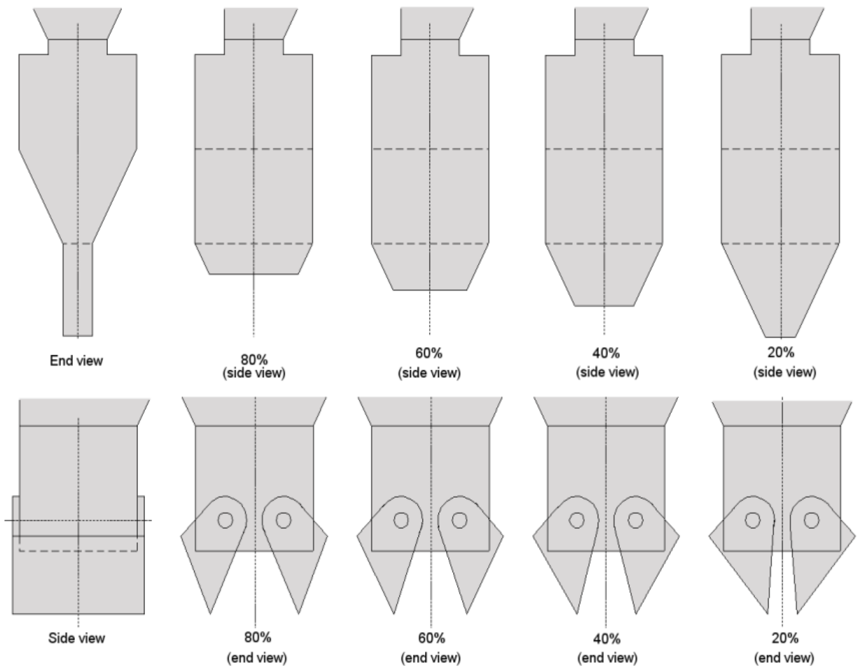

Fig 4 Diagram illustrating changes in geometry associated with reducing aperture – system 2 (detergent) top & system 1 (coal) bottom

It was considered that the discharge behaviour detected in system 1 was due to the induction of air into the outlet from the open ends of the doors and through the clearances along the tops of the doors when in an open position. Air induction was considered to be a major factor in the accelerated flow behaviour and thus future work to be undertaken using a revised test rig would attempt to investigate this effect more fully through the establishment of an intentional induction path for air.

System 2 was operated using a range of outlet sizes and it could be observed that at 80% aperture (using a truncated secondary plane flow section under a full plane flow feed hopper) a contraction of the discharging stream of particles occurred along the sides of the outlet, whilst the bed of particles acting against the convergent end walls remained deformation free (Fig 5a). Reducing the outlet size to 60% (Fig 5b) produced a much stronger deformation of the discharge stream and yielded an increase in flow rate that exceeded that achievable for the 80% aperture. Decreasing the outlet size to 40% resulted in the resumption of a deformation free discharge of particles (Fig 5c).

Figs 5a, 5b   Photos showing deformation generated during reductions in aperture size for system 2 (80% left & 60% right)

Fig 5c   Photos showing deformation generated during reductions in aperture size for system 2 (40% aperture)

The reduction in aperture size was achieved by changing the outlet geometry by reducing the slot length whilst simultaneously altering the length of the fixed angle end walls to increase the depth of the secondary plane-flow section (effectively by replacing pyramidal slices that formed the secondary plane-flow section).

Before considering the model for the discharge behaviour it is important to appreciate that during discharge from a mass flow vessel, the particles that comprise a bulk solid in the convergent section of a vessel will dilate. During this process the interstitial gas present in the voids between the particles will increase in volume and thus generate a negative pressure (this effect being influential for fine material that generally exhibits poor permeability). Research work investigating this effect and the influence over discharge rates has been undertaken by many researchers – of which the work by Ghu et al [4] is notable and from which Fig 6 is taken to illustrate the effect.

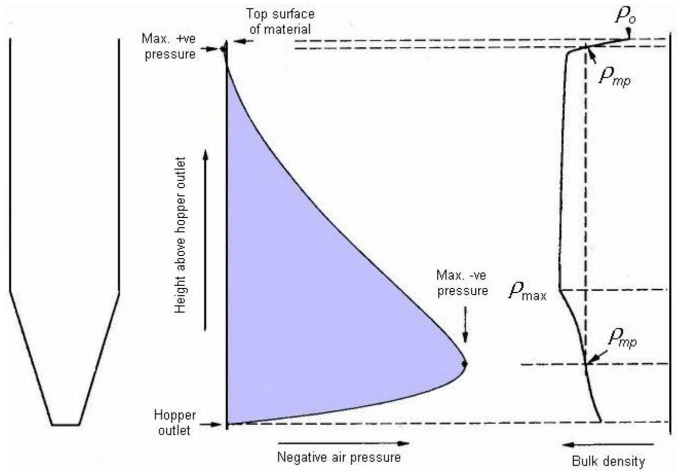

Fig 6 Typical distributions of air pressure and bulk density in a vessel (Ghu et al [4])

3. DISCUSSION

An explanation for the deformation of the discharging material is that if no secondary plane flow section were present, the powder discharge rate would be defined by the outlet of the plane flow feed hopper and would be subject to conventional flow behaviour. The interposition of a secondary plane flow section (at 80% aperture) imposes a short convergent wall at each end of the slot against which discharging material shears (and decelerates).

Due to the natural induction of air (generated by the negative pressure developed in the interstices of the bulk particulate) upwards into the outlet as the powder dilates, the denser flow of material at the ends of the slot represents a higher resistance to air ingress than the material exiting from the plane flow feed hopper (with a vector velocity from the convergent side walls) – thus the "necking" in of the discharge stream is partially supported by air being drawn into aperture along its main axis. However, by increasing the depth of the secondary plane flow section (creating a 60% aperture) additional changes relating to the interaction of air and geometry occur. Deepening of the section generates significant vertical walls extending down from the outlet, combined with longer fixed angle walls. This change in wall proportions relative to aperture size has two main effects. Firstly, the bed of material flowing down the end walls generates an increased velocity profile towards the flowing material in the central region of the slot, whilst the vertical side walls act as a channel and impart a vectored delivery of inducted air vertically into the vicinity of the outlet. Extrapolation of the resulting deformation of the discharging material suggests that the flow rate of air is sufficient to penetrate into the feed hopper to a point above the outlet. Having established this penetration into the bed of particles, a dispersion of negative pressure void gases ensues providing a significant dilation of the powder. Thus the powder fails at a position on the convergence above the outlet – effectively converting the function of the lower section of the feed hopper and the secondary plane flow section into that of a chute. This model serves to explain why flow rates can be boosted to levels only associated with significantly larger outlet sizes and is directly attributable to the establishment of a deliberate vena contracta effect for the discharging bulk particulates. The imposition of a deeper section combined with narrowing the aperture results in a deepening of the bed of particles flowing down the end walls to a point whereby the two beds interact and choke the induction of air.

An evaluation of the influence of interstitial gas pressure upon the vena contracta effect was undertaken by modifying the gas pressure of the voids prior to the outlet. In this particular case air was introduced at the walls of the feed bin at a height of approximately 200mm above the outlet. The quantity of air injected for this trial was 3% by volumetric discharge rate of the bulk solid (based on its poured bulk density). The injection of air caused a reduction in the level of vacuum developed in the interstices and as can be seen in Fig 6, brought about a partial elimination of the vena contracta. This simple test condition supports the assertion that a primary influence of the establishment of the discharge phenomenon is the level of void gas pressure in the flowing bulk particulate.

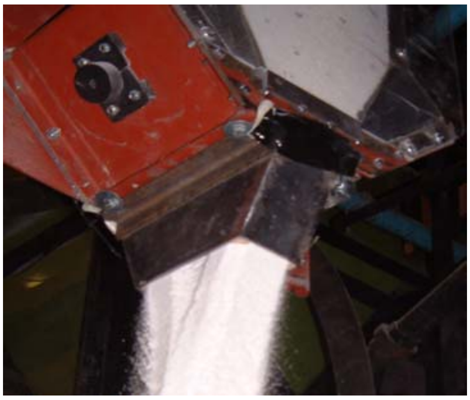

Fig 6 Image showing the partial elimination of the vena contracta through increased void gas pressure in the feed hopper

4. FURTHER WORK

Having identified the vena contracta effect and measured the increased flow rate that results from its establishment, further research work is currently underway at The Wolfson Centre for Bulk Solids Handling Technology. Although the level of vacuum in the interstices has been identified as a key factor, additional work is required to fully understand the influence of the level of friction generated against the convergent end walls, the permeability of the bulk particulate and the velocity profile generated from the end walls towards the centre line of the outlet.

5. APPLICATION TO INDUSTRIAL PROCESSES

The implication of using equipment specifically designed to discharge bulk particulates with a high flux density (using the vena contracta effect), is primarily that supplementary air usage commonly associated with handling fine powders can be eliminated. One of many problems commonly linked to discharging fine powders into processes such as bag filling or tanker filling, is that excessive quantities of air are commonly injected into the powders in order to obtain flow. The injected air will invariably be discharged with the powder from the hopper discharge section resulting in low bulk density deliveries of powder, inconsistent flow rates, high dust levels and (in the case of sack filling) poor bag stability and sealing efficiency. The instrumentation used in many process control systems also exert poor control due to the variability of the quantities of in-flight material induced by excessive aeration. The net result of handling over-aerated materials is that flow control and metering functions can become severely impaired.

The main benefit of discharging at a very high flux density is that not only is dust generation reduced (by virtue of the less dispersed flow stream), but also that in-flight consistency is improved at the operating point where the vena contracta occurs - at 60% aperture (see Fig 7 for discharge rate comparison and Fig 8 for variability). The main reason for the increased variability induced by the injection of additional air into the flowing bulk particulate can (in the authors' opinion) be attributable to the pre-outlet dilation that occurs inside the convergent section. This early initiation of the dissipation of negative void gas pressures gives rise to a reduced intensity of particulate packing – giving rise to a high velocity exit stream of material at a relatively low flux density. For the tests that were undertaken, the total collapse of the vena contracta was not achieved by the introduction of additional air suggesting that some low level vacuum was still occurring. The result of the presence of a partial vacuum was that air induction would still occur to bring about a state of pressure equilibrium. In turn this would locally influence flow behaviour by virtue of the air counter flow effect noted by many previous research works [5, 6] and hence bring about variability in the discharge rate.

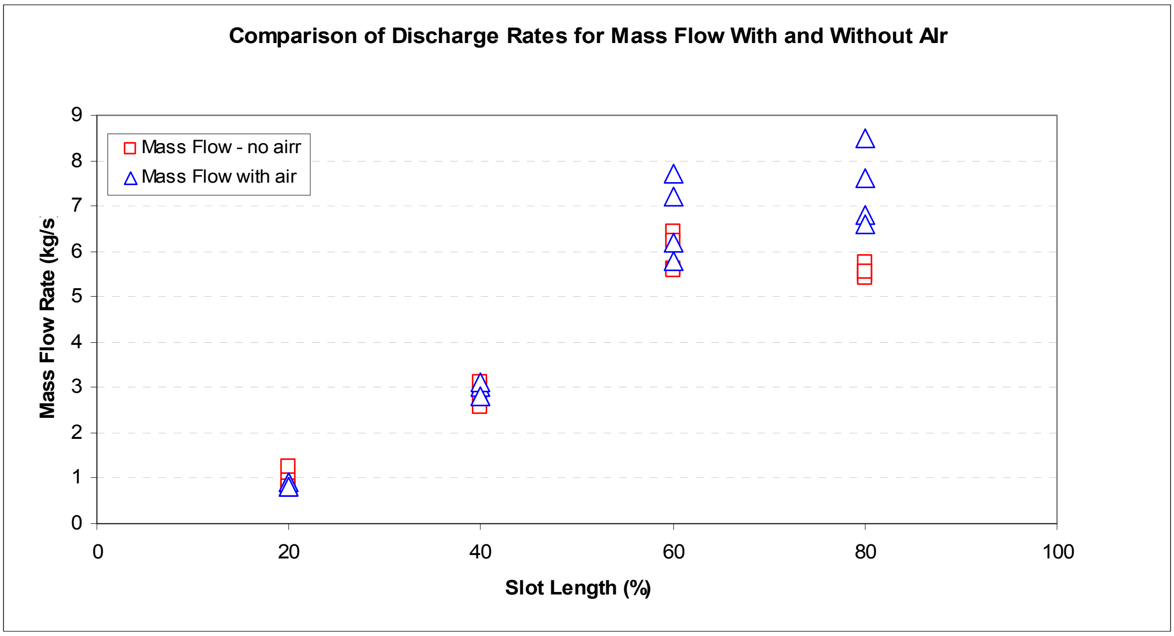

Fig 7 Relative discharge rates for a double plane flow vessel being operated with and without additional aeration

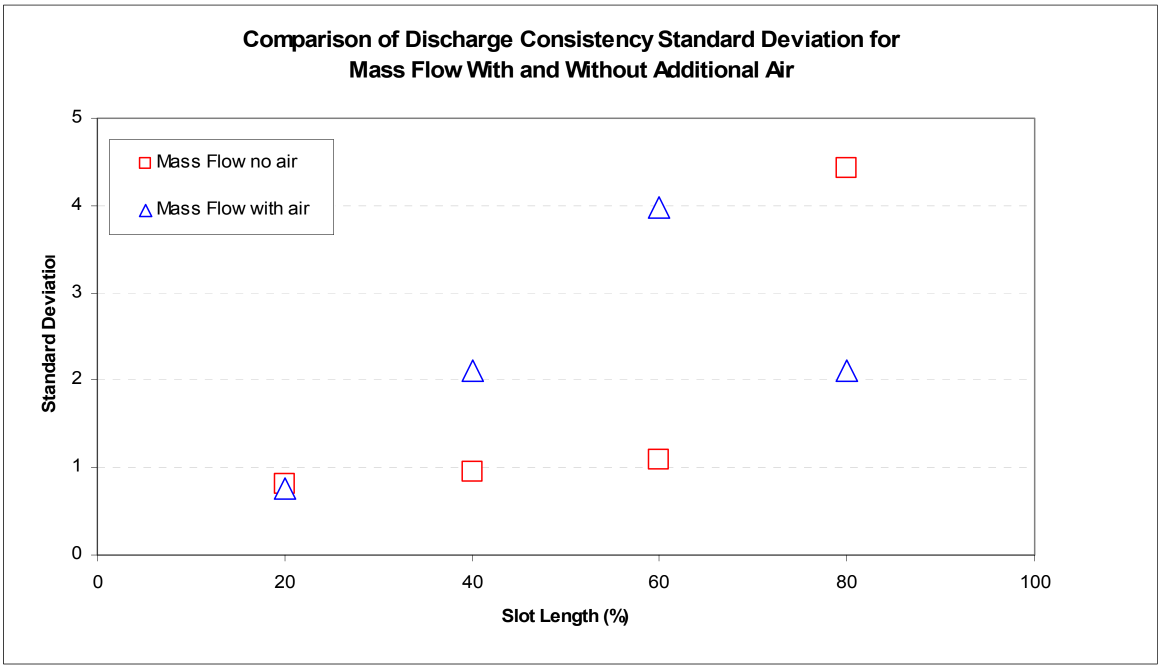

Fig 8 Relative discharge consistency for double plane flow vessel being operated with and without additional aeration

The generation of a high flux density discharge can therefore be seen to offer additional benefits in terms of increased discharge consistency combined with reduced susceptibility to air interaction (leading to reduced fugitive fine generation in the vicinity of the discharge operation).

6. SUMMARY

A previously unreported discharge phenomenon has been found and fundamental research into the causes has been undertaken. The discharge behaviour results in the generation of a high flux density discharge of material in the form a vena contracta and has been found to not only give higher discharge rates than would be normally associated with a given aperture size, but to offer greater flow consistency at this operating point. There are many industrial applications where a gravity driven feed of bulk particulates is required and engineering equipment to produce this discharge behaviour would be beneficial.

These benefits include.

- the current level of research undertaken has demonstrated that the effect can be generated repeatably for widely different particle types,
- the powder will only draw in sufficient air to bring the void gas pressure into equilibrium with the local environment (thus the powder is dilated to an optimal condition without the over-aeration associated with many industrial processes),
- the elimination of the need for supplementary aeration techniques means that filling operations (bags, tankers, etc.) can be performed to a greater volumetric efficiency,
- the establishment of a boosted discharge rate above that associated with a given aperture size means that filling of containers with flow limiting inlet sizes can be achieved more rapidly,
- the strong induction of air can be used to re-entrain fugitive fines back into the discharge stream,

- bag filling operations can be undertaken more accurately due to the consistency of discharge combined with improved bag stability due to reduced air requirements.

An international patent relating directly to the intentional establishment of this discharge phenomenon for process advantage and additional uses of the phenomenon have been granted to The University of Greenwich[3].

7. REFERNCES

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