15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

Air Entrainment by Free Falling Streams of Particles

Zeqin Liu, Paul Cooper and Peter W Wypych
School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, NSW 2522, Australia

Abstract

This paper describes a study of free falling streams of particles or "particle plumes". Experiments in air were carried out to determine the volumetric flow rate of entrained air as a function of drop height, mass flow rate and particle properties. Flow visualisation observations of the particle plumes are presented that show how the stream of particles descends in a dilating "core" of relatively constant radius after an initial contraction immediately below the source. The void fraction of the falling particle stream appears to increase homogeneously with height to a given point, but then the stream breaks up into a train of distinct particle "clouds" that descend and disperse. A theoretical model of the flow in such particle plumes is described whereby both entrained air flow rate and particle velocities are predicted for the situation where the core dilates homogeneously.

Introduction

Powders and granulated solid handling systems are widely used in industry for bulk solid materials storage, handling and transportation. Industries relying heavily on these systems include agriculture, mining, chemical engineering, power plants, cement and food processing. There are many bulk solids handling processes that involve free fall of the particles (e.g. silo filling, conveyor transfers, powder mixing/processing). When a stream of particles free fall, the surrounding air is induced to flow with the particle stream as the bulk solid accelerates and expands. The entrained air forms a jet or boundary layer around the falling "core" of bulk material. The radius of this boundary layer grows with increasing drop height and may carry with it fine, fugitive dust particles.

Relatively little fundamental research has been carried out on the fluid and particle mechanics of these "particle plumes" which have some similarities with other plume and jet flows such as bubble plumes and water sprays [1,2] in that they are two-phase, non-Boussinesq problems. The purpose of the present research is to develop predictive tools for designers of dust control systems and to further the understanding of an important fundamental fluid flow situation. Articles have appeared in the past literature on air entrainment by falling streams of particles, notable that by Hemeon [3] who predicted air entrainment rates by extrapolating from the case of air entrained by a single, isolated particle free-falling through quiescent ambient air. The theory of Hemeon was later applied and modified by Morrison [4] and Tooker [5]. More recently work in the US by Plinke *et al.* [6] and at the University of Wollongong has focussed on quantifying the practical situation where falling streams of common bulk materials entrain air and work on determination of the velocity profile of the entrained air has been previously reported [7]. In this paper results of recent experiments are presented and the development of a theoretical model of the behaviour of particle plumes is discussed.

Experimental Apparatus

The experimental rig was designed to permit the quantitative evaluation of the flowrate of air entrained by a falling stream of bulk material by allowing the stream to pass into a sealed enclosure through an aperture (Figure 1). Induced and displaced air was extracted from the enclosure and the extraction flow rate was adjusted so that there was no static pressure difference between the chamber and the ambient air. The experimental methodology was validated by first replicating the results of Ricou and Spalding [8] by measuring the induced air flowing through the aperture from an isothermal jet generated by a nozzle where the hopper is located in Figure 1 [9]. The mass flowrate of bulk materials was maintained approximately constant during each test by means of the double-hopper arrangement, the test bin being flooded by the storage bin. The entire hopper system was suspended from a frame so that the mass flow rate of material could be measured directly by means of load cells attached to the suspension cables.

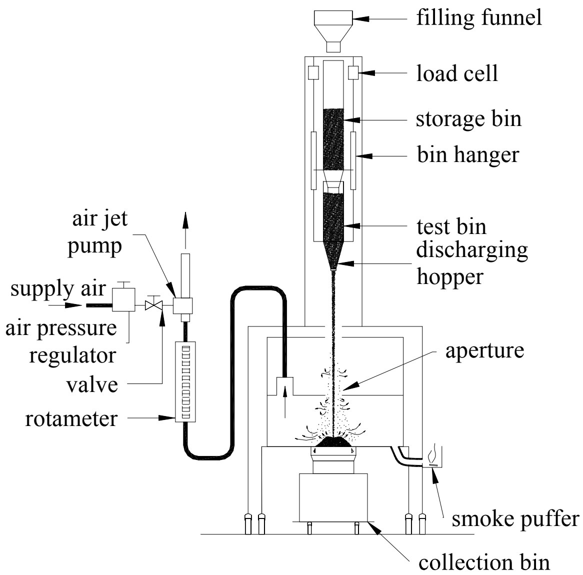


Figure 1. Schematic of the experimental apparatus.

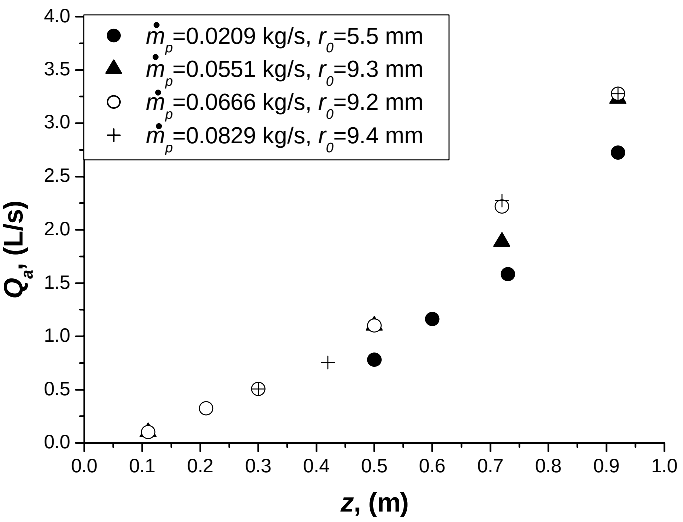
Pressure equilibrium between the surrounding air and the inside of the chamber was determined by smoke visualization at a pressure observation port. To maintain a constant height of stockpile during each experiment, a collection bin was installed to receive the excess particles from the stockpile through an annular slot. The rig frame could be lifted up to adjust drop heights for various tests. The particulate mass flow rate was varied by changing the diameter of the outlet of the discharging hopper. Three bulk materials were tested: alumina powder, sand, and corvic vinyl powder with median particle diameters of 96μm, 367μm and 116μm and particle densities of 2465kg/m^3, 1400kg/m^3 and 1487kg/m^3, respectively. Bulk solid mass flow rates between 10grams/s and 83grams/s were employed for this section of the work.

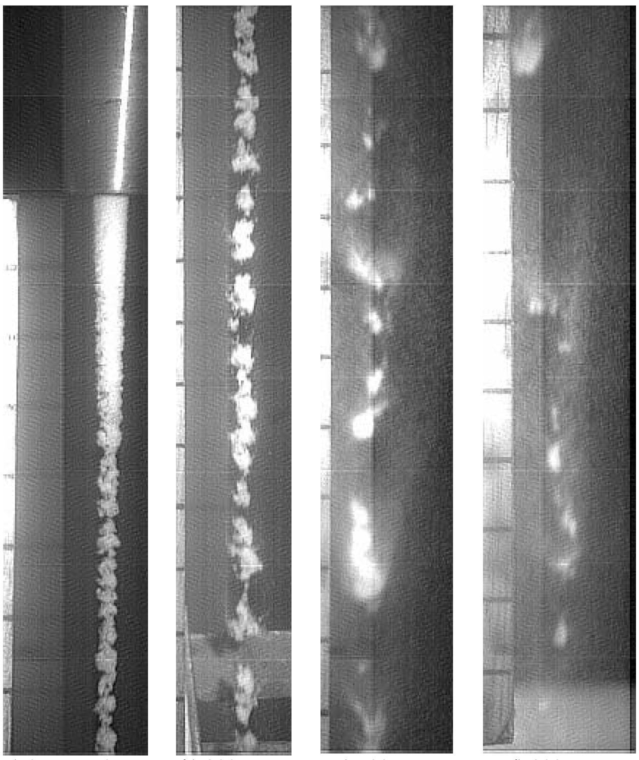
A visualisation study of the nature of the particle stream flow was also undertaken. The velocity of the free-falling particles was estimated by video recording the particle stream using a Phantom high speed video camera with a frame rate of 1635Hz. Consecutive images were then analysed to estimate particle velocities using the Insight PIV software system (TSI Inc.). The quantitative accuracy of this system was relatively limited due to the limited resolution of the high speed video camera. However, the data provided important information on both the qualitative and quantitative behaviour of the free falling particle stream. The bulk solid material mass flow rates for this work were relatively small (~ 1gram/s where the hopper outlet radius 1.0mm < r_0 < 2.5mm).

Experimental Results

The volume of entrained air increased with increasing drop height and the specific entrainment volume (volume of air entrained per mass of particulate) decreased significantly with increasing mass flow rate. The results for a series of tests on the alumina powder are shown in Figure 2.

Figure 2. Air entrainment variation with drop height and mass flow rate for alumina powder.





a) 0 < z < 70mm b) 200 < z < 300mm c) 700 < z < 900mm d) 900 < z < 1000mm

Figure 3 Free-falling alumina particle stream: r_0 = 2.5mm, $\dot{m}_p$ =3.8g/s

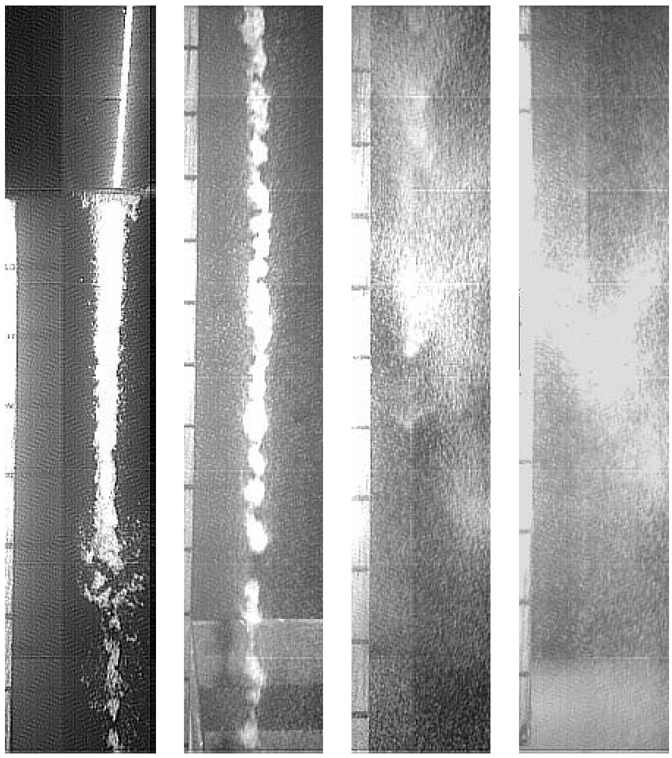
(scale to the left is marked in 10mm increments)

.

An example of images of the falling stream recorded by means of the high speed digital camera are shown in Figures 3 and 4. The falling streams of particles appeared to have three zones of development. In the initial stages of free fall, Zone 1 (Figure 3a), the radius of the particle stream contracted immediately after leaving the hopper. This contraction is most likely to have been due to the fact that the conical sides of the hopper outlet imposed an initial inward radial velocity on the outer particles in the stream.

After the initial contraction, the radius of the core of falling particles remained relatively constant (Zone 2) over a very large elevation (to at least $z/r_0 \sim 200$). A significant feature of the flow was the fact that the dilation of the particulate material was not homogeneous, and the core of the stream appeared to break into a series of individual particle "clouds", as shown in Figures 3 and 4. Often this breakup appeared to have a preferred length scale, analogous to the breakup of a thin stream of liquid falling through air under gravitational forces where surface tension plays a role in determining droplet size. The particle clouds appeared to disperse with increasing drop height and were more readily dispersed at low particle mass flow rates, $\dot{m}_p$.

At large *z*, in Zone 3, the particle "clouds" were no longer evident as distinct elements. This region was only observed if there was a sufficiently large drop height or a sufficiently small particle mass flow rate. Moreover, it was difficult to capture the behaviour of this region with the video recording apparatus available. The behaviour of the particle-driven plumes clearly had characteristics similar to that of particle-driven thermals as described by Rahimipour and Wilkinson [10].



a) 0 < z < 70mm b) 200 < z < 300mm c) 700 < z < 900mm d) 900 < z < 1000mm

Figure 4. Corvic vinyl particle stream: r_0 = 2.5mm, $\dot{m}_p$ =2.0g/s

The breakup behaviour of the particle stream was also dependent to some extent on the properties of the bulk material. This is illustrated by a comparison of Figures 3 and 4. Figure 4a shows an energetic breakup event close to the hopper outlet and Figures 4b-d indicate that the corvic vinyl clouds may disperse more rapidly than those of alumina.

Theoretical Model

The following one-dimensional analysis was developed by considering the momentum equations for both the falling particles and the induced air, which are coupled through the aerodynamic drag forces. Clearly the particle plume flow is complex and a one-dimensional model to predict particle velocities, air entrainment velocity and volumetric flow rate must involve simplification of the flow phenomena. The aerodynamic force acting on a single particle within a stream of particles, for example, is very different from that acting on a single, isolated, falling particle. The inter-particle distances can be very small, particularly near the source of the particle plume, and the drag force acting on a particle is far from constant with respect to drop height. Moreover, the experimental results reported above show that the dilation of the particle stream may not be homogeneous beyond a given drop height. Nevertheless, the authors believe that the theoretical model represents valuable step toward the goal of understanding the behaviour of the particle plumes.

Consider a particle stream released from a source of radius r_0 where n is the number of particles released per unit time. If at some elevation z the particles move with velocity v_p then the total drag force acting on these particles is given by [9]:

$$F^* = n \times f_d \times C_S \qquad (1)$$

where f_d is the drag that would act on a single, isolated particle falling at velocity v_p through quiescent air, and C_s is a "stream coefficient", which we have introduced to represent the ratio of the drag force acting on a particle within a stream of particles compared to that for an isolated particle. If all particles are then treated as being aerodynamically equivalent to spheres of diameter d_p and density ρ_p, then:

$$F^* = \frac{3\pi}{4d_p}\beta_0 v_0 r_0^2 \rho_a (v_p - v_a)^2 C_D \times C_S \qquad (2)$$

where, β_0 is the volume fraction of solid particles in the bulk solid, v_0 is the bulk solid velocity at the source, ρ_a and μ_a are the density and dynamic viscosity of air, respectively, v_a is the local characteristic vertical velocity of the air in the falling stream and C_D is the drag coefficient for a single isolated particle.

We have utilised the results of Wen and Yu [11] who carried out an experimental study on fluidized beds. We have assumed that their results are representative of the present situation in the core of the unconfined particle plume and that the stream coefficient C_s is a function only of the volumetric void fraction, $\varepsilon = (\rho_p - \rho_b)/(\rho_p - \rho_a)$, such that $C_s = \varepsilon^{-4.7}$. The net buoyancy force acting on the n particles released in one second, B^*, is then given by:

$$B^* = (\rho_p - \rho_a)\pi g \beta_0 v_0 r_0^2 \qquad (3)$$

Invoking conservation of momentum on the particles falling under the influence of gravitational forces gives the rate of change of particle velocity with height:

$$\frac{dv_p}{dz} = \frac{B^* - F^*}{\dot{m}_p v_p} \qquad (4)$$

The development of the jet or boundary layer of entrained air may be modelled in the same way as for miscible jets/plumes by making the assumption that the horizontal velocity of the entrained air is directly proportional to a local vertical velocity scale [12]. The constant of proportionality being the "entrainment constant" (α) so that:

$$\frac{d}{dz}\left(\pi r_a^2 v_a\right) = 2\pi r_a \alpha v_a \qquad (5)$$

where r_a and v_a are the "top hat" radius and velocity of the entrained air jet. The rate of change of momentum flux of the entrained air with height may then be determined. Since the flow is isothermal only drag forces from the particles act on the air and the drag force on the air per unit height is then F^*/v_p. The rate of change of momentum flux is then:

$$\frac{d}{dz}\left(\rho_a \pi r_a^2 v_a^2\right) = \frac{F^*}{v_p} \qquad (6)$$

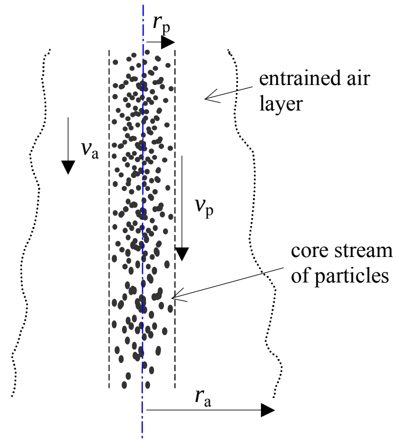


Figure 5. Schematic of the particle stream with the dilating stream of particles of constant stream radius, r_p, and surrounding entrained air.

The determination of the local value of void fraction is an important issue in the theoretical model, because this influences the magnitude of drag forces on the particles. The model above quantifies the particle velocity but the radius of the particle stream, r_v, also needs to be known. From the visualisation experiments described above it is clear that this radius is constant with respect to height for at least for much of Zones 1 and 2. We have therefore assumed that r_v, ~ r_0, However, for this model the complexities of the particle clouds have been put aside and the particle stream is assumed to dilate homogeneously. Equations (4)-(6) were then solved using a finite difference scheme.

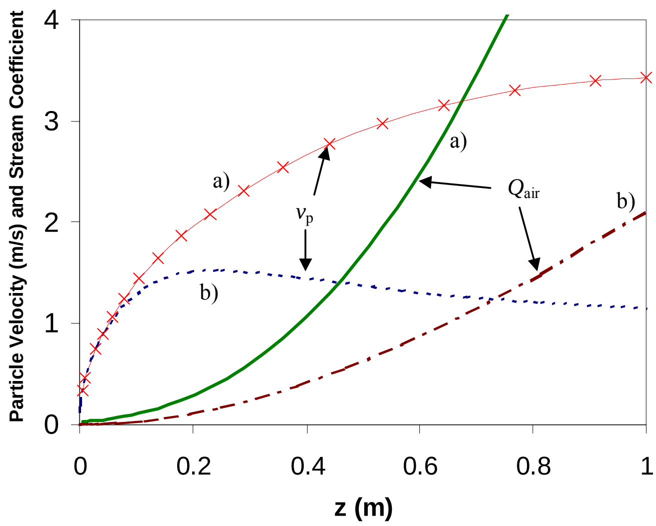


Figure 6. Entrained air flow rate and particle velocities predicted by the theoretical model for an arbitrary bulk solid (d_p = 100μm, ρ_p = 1500 kg/m^3, ρ_b = 500 kg/m^3, α = 0.03) with two different solid mass flow rates: a) $\dot{m}_p$ = 20g/s; b) $\dot{m}_p$ = 0.2g/s.

The results of this theoretical model are shown in Figures 6 and 7 for a bulk solid of arbitrary physical properties. Figure 6 shows how the particle velocity as a function of elevation is critically dependent on the particulate mass flow rate. At the higher mass flow rate the particles continue to accelerate over the full height of the simulation (1.0m). However, at the smaller mass flow rate the particles reach a maximum velocity at $z \sim 0.2$m and thereafter tend towards a lower velocity. This behaviour has been observed qualitatively in the flow visualisation experiments as shown in Figure 8. A further insight into the behaviour of the plume can be seen in Figure 7 where the velocity of the particles relative to the air approaches the terminal velocity as expected.

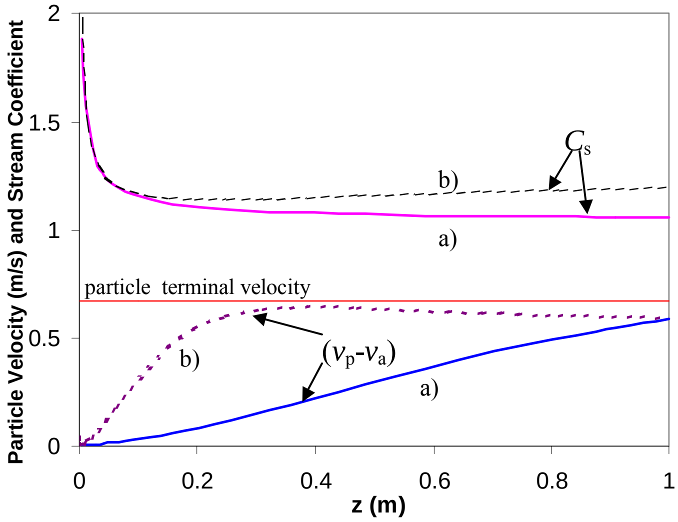


Figure 7. Relative velocity of particles ($v_p - v_a$) and stream coefficient, C_s, predicted by the theoretical model for an arbitrary bulk solid (details as for Figure 6).

The entrainment constant α for each material was determined by fitting the theoretical model to the air entrainment experimental data using the least squares method. Figure 8 shows a comparison of the predicted and measured entrained air flow rates for typical set of experiments on alumina. Note that the particle diameter used in the numerical model was taken to be the median particle size of a representative sample of the bulk material. The theoretical model above provided a good correlation of the experimental data with a single entrainment constant for each material. However, α did vary significantly between the materials: $\alpha_{alumina} = 0.0196 \pm 0.004$; $\alpha_{sand} = 0.0210 \pm 0.007$; $\alpha_{coriv\_vinyl} = 0.0326 \pm 0.006$. These entrainment rates are less than for miscible jets and plumes ($\alpha_{jet} \approx 0.0535$, $\alpha_{plume} \approx 0.083$).

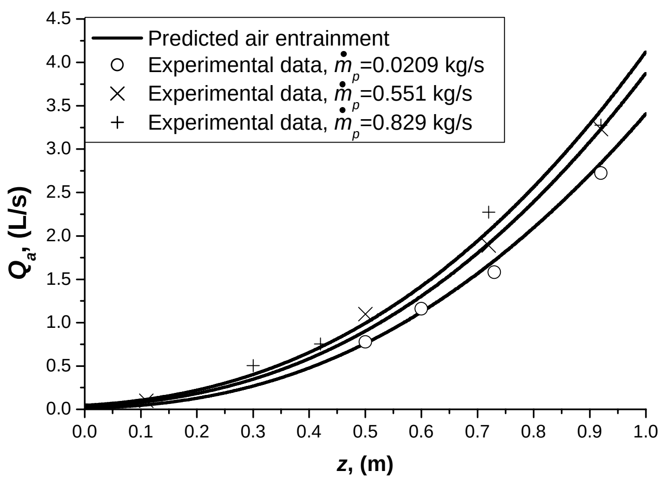


Figure 8. Variation of entrained air flowrate against particle drop height, alumina ($\alpha = 0.0196$, $d_p = 96$ µm).

Further work is required on the theoretical analysis to incorporate some of the details of the flow not covered above, while there is also a need for further experimental work to determine the particle velocities within the falling stream over all three zones.

Conclusions

Free falling particle streams, or particle plumes, are important in many industrial situations. This paper has outlined a program of experimental work that has determined the characteristics of such falling streams in air, at laboratory scale, with respect to the quantity of air entrained as a function of height, particulate mass flow rate and physical properties.

High speed video imaging of the free-falling particle stream has also shown that the bulk material does not dilate in a homogeneous manner, but rather the core stream of bulk material appears to break up into a series of particle "clouds" that disperse with increasing drop height. There also appears to be three major zones in the vertical development of the particle plume. In Zone 1 near the source the core stream of particles descends with a slight decrease in radius and appear to dilate homogeneously. Below this region, in Zone 2 the core stream breaks up into distinct particle clouds. And finally in Zone 3 these clouds become increasingly dispersed and the core stream radius increases markedly.

A theoretical analysis of the air entrainment process has been developed that models the drag forces on the particles within the falling stream and predicts the particle velocity and entrained air flow as a function of drop height, particulate mass flow rate and particulate properties.

References

[1] Leitch, A. M. and Baines, W. D., Liquid volume flux in a weak bubble plume, *J. Fluid Mech*, **205**, 1989, 77-98.

[2] Gosh, S., Hunt, J.C.R., Phillips, J.C. and Miller, P.C.H., Dynamics of turbulent air-flow in droplet driven sprays, *Appl. Scientific Res.*, **51**, 1993, 257-262.

[3] Hemeon, W. D. L., *Plant and process ventilation*, Industrial Press, N.Y, 1963.

[4] Morrison, J. N., Controlling Dust Emissions at Belt Conveyor Transfer Points, *Society of Mining Engineers, AIME, Transactions*, **250**, 1971, 47-52.

[5] Tooker, G. E., Controlling fugitive dust emissions in material handling operations, *Bulk Solids Handling*, **12**, no. 2, 1992, 227-232.

[6] Plinke, M.A.E., Leith D., Holstein D.B. and Boundy, M.G. *Am. Ind. Hyg. Assoc*. J., **52**(12), 1991, 521-528.

[7] Cooper, P., Liu, Z. and Wypych, P. W., Plumes Driven by Free-Falling Streams of Solid Particles, *Proc. 14th Australasian Fluid Mechanics Conference*, Adelaide, 2001, 649-652.

[8] Ricou, F.P. and Spalding, D.P., Measurements of entrainment by axisymmetrical turbulent jets, *J. Fluid Mech.*, **8**, 1961, 21-32.

[9] Liu, Z., *Air entrainment in free falling bulk materials*, PhD thesis, University of Wollongong, Australia, 2003.

[10] Rahimipour, H. and Wilkinson, D., Dynamic behaviour of particle clouds, *Proc. 11th Australasian Fluid Mech Conf., Hobart, Australia*, 1992, 743-746.

[11] Wen, C. Y. and Yu Y. H., Mechanics of Fluidization, *Chemical Engineering Progress, Symposium Series*, **62**, 1966, pp. 100-111.

[12] Morton, B., Taylor, G.I. and Turner, J.S., Turbulent gravitational convection from maintained and instantaneous sources, *Proc. Royal Soc. London, A*, **234A**, 1956, 1-22.