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Dust emission in powder handling: Free falling particle plume characterisation

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ABSTRACT

Dust generation during solids handling, principally from the free falling of bulk materials and their impact on stockpiles, can be a health threat for operators and a cause of dust explosions. The proper design of a dust emission control system requires knowledge of the behaviour of the free falling jet, in particular the amount of air entrained by the falling powder and the concentration of dust liberated. The focus in this present paper is on the effect of drop height of a free falling jet on segregation by particle size, particle velocity, changes in particle concentration and entrained air in the dust plume. This gives a quantification of the important parameters and the concentration of dust emitted during a free fall.

1. Introduction

Bulk material handling operations involving a falling stream of particles are very common in industry. In such operations, fine particles contained in the bulk material break away from the main flow and become mixed with ambient air causing airborne dust. Such dust emissions can cause a number of problems in industry such as dust explosions and risks for operator's health.

The most common methods used to control dust are ventilation and moistening. However, in many industrial processes, the method of moistening products is not acceptable. Therefore, a well-designed ventilation system may offer a solution to capture the dust emitted from the working process. However, in the absence of knowledge of the mechanisms of dust generation and how much dust is generated, the design of such systems is mainly based on empirical methods.

There are two principal physical mechanisms whereby dust leaves the bulk material and is carried away from the stockpile by air currents: (a) dust liberation during the free fall of the parent material, (b) impact of a falling stream on a stockpile releasing the entrained air that causes pulvation of fugitive dust from the stockpile [1]. This study investigates only the first phenomenon.

When a stream of particles is in free fall the surrounding air is entrained into the particle stream (Fig. 1), the bulk solid expands, and the voidage of the stream increases. Due to the turbulent airflow around the stream of material, some particles, particularly the smaller particles, mix with the entrained air to form a dust laden "boundary layer" around the falling core of bulk material. As the fall distance increases, the turbulent motion of the surrounding air causes the smaller particles to invade the boundary layer of the falling stream [2] and the radius of this dust boundary layer grows with increasing drop height [3].

This flow phenomenon is quite complex and of primary importance for the design of any dust control system. The relevant parameters include the volume of air entrained (and hence the air extraction rate required in an industrial ventilation system), the dust concentration in the contaminated air and the location of this contaminated air (to optimise the extraction point). The present paper focuses on these parameters in order to develop quantitative tools for dust control system design dealing with falling streams of bulk materials.

The first approach to this problem was by Cooper and Arnold [1]. The work presented here is the continuation of this and in particular that of Liu et al. [3]. Liu built an experimental rig (as described later) to measure the air entrainment in a free falling stream of particles and he established the basic equations of this two-phase flow [4]. Here, we complete these experimental results by measuring the particle concentration and particle velocity migration, and the changes in particles size distribution in the plume by optical measurements and weighing, in order to estimate the concentration of powder broken away from the main flow. Furthermore, we have validated Liu's equations by using a Particle Image Velocimetry (PIV) system [5].

2. Experimental

The experimental set up comprises a stainless steel silo of 20 cm diameter and 60 cm height (Fig. 2). It is filled by a pneumatic

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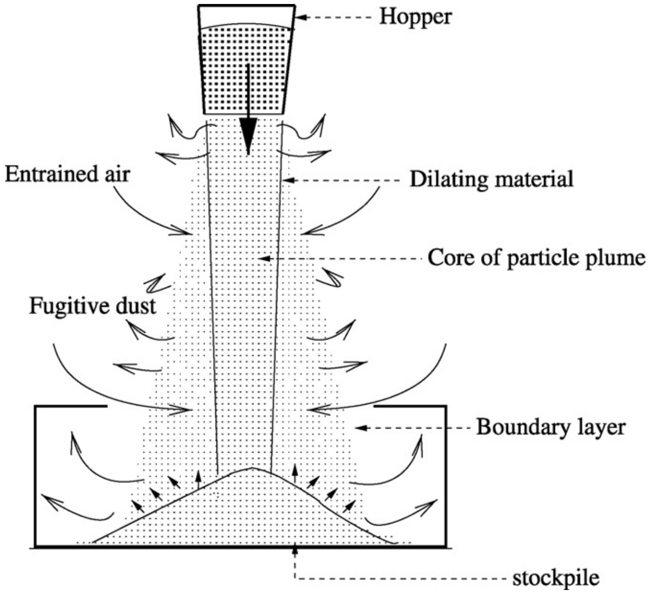

Fig. 1. Dust generation for falling stream of material.

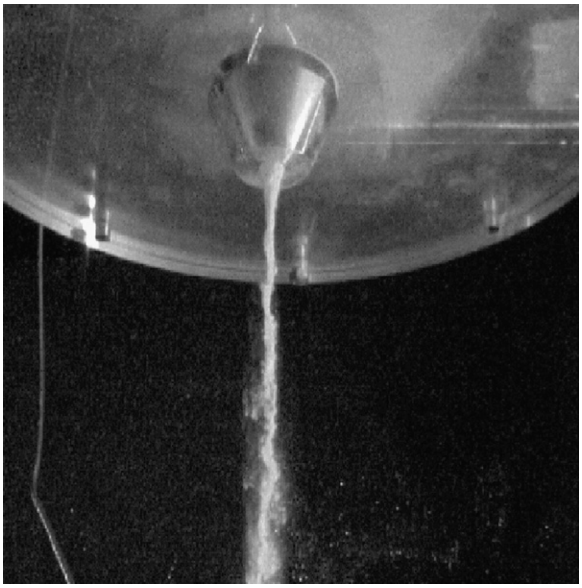

Fig. 3. Photo of the first 30 cm of a powder stream from the hopper outlet.

conveyor positioned above it. The silo has a conical Perspex outlet with a semi-angle of 30°. Different outlet diameters can be used to produce different mass flow rates of powder (Fig. 3). This silo is mounted on three mass sensors to continuously weigh its contents during discharge and thus determine solids flow rate.

The quantity of air entering into the hopper to replace the corresponding volume of flowing bulk material, is measured by an airflow rate sensor placed on a vent at the top of the silo.

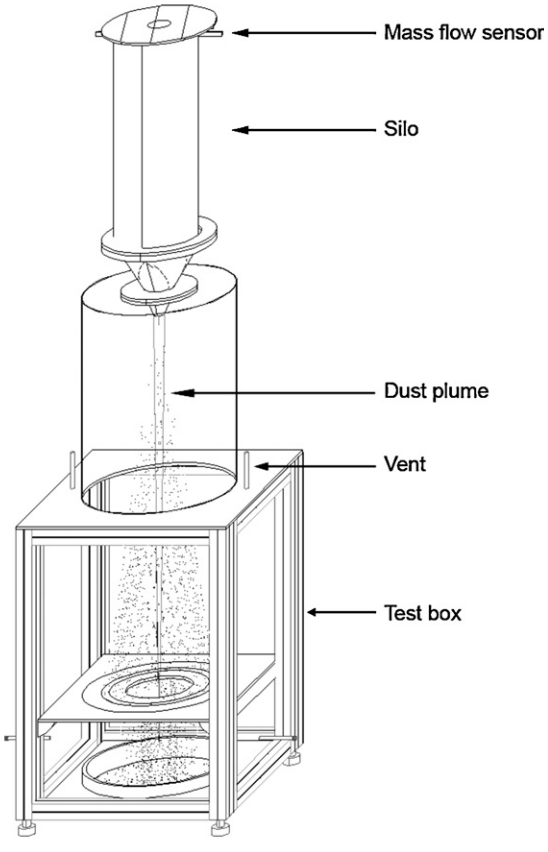

Fig. 2. Sketch of the experimental set up.

The particle stream flows from the silo outlet down through an empty quasi-cubic box of size 1 m^3 to obtain a free fall of particles. This box is divided into two parts by a horizontal plate with an orifice in it. The size of this orifice can be changed to separate the dust emitted during the free fall from the dust emitted by the impact on the stockpile (Fig. 2). Two vents have been put on the top part of the box to allow the plume to expand freely as if in quiescent ambient air. It was necessary to ensure that the vents were large enough to avoid pressure reduction by the entrained air, which would contract the falling stream. For this, a pressure sensor is used to check that the air pressure between the top of the test box and the ambient environment remains constant. Two vents have been put on the bottom part of the box to avoid an over-pressure generated by the particles impacting on the stockpile. The size of these vents was fixed by using a pressure sensor in the same way as mentioned above. This box is mounted on a frame that can be raised or lowered to change the drop height.

A Spraytec laser granulometer (Malvern Instruments) located in the top part of this box is used to obtain the particle size distribution of fine and coarse particles in the falling stream and the plume. This instrument provides in situ analysis of the volume concentration using the Beer–Lambert law and size distribution from the scattered light. To enhance its spatial resolution, the beam has been reduced from 10 to 6 mm with appropriate lenses. This device is mounted on a Y–Z table to access the different heights and depths in the falling plume of dust.

A PIV system is also located in the top part of this box to measure the particle velocity field by determining the particle displacements (Δx, Δy) in the flow over a given time $\Delta t = 100\,\mu\text{s}$. A pulsed laser sheet, generated by a Nd:YAG laser (wavelength: 532 nm, energy/pulse: 30 mJ, pulse duration: 4 ns and frequency: 15 Hz), illuminates a plane in the flow (Fig. 4) and the position of the particles are recorded. A second laser pulse Δt later illuminates the same plane, creating the second set of particle images. These particles' movements are captured by the image capture system and recorded as image displacements. The CCD camera has an asynchronous double exposure mode and is able to acquire images up to 30 Hz pulse repetition rate.

Two other kinds of measurements are carried out in the lower part of the receiving box. The first is to study the plume mass fraction of particles in the plume: the stream of particles falls through an observation zone into the box, described above, with lid having a

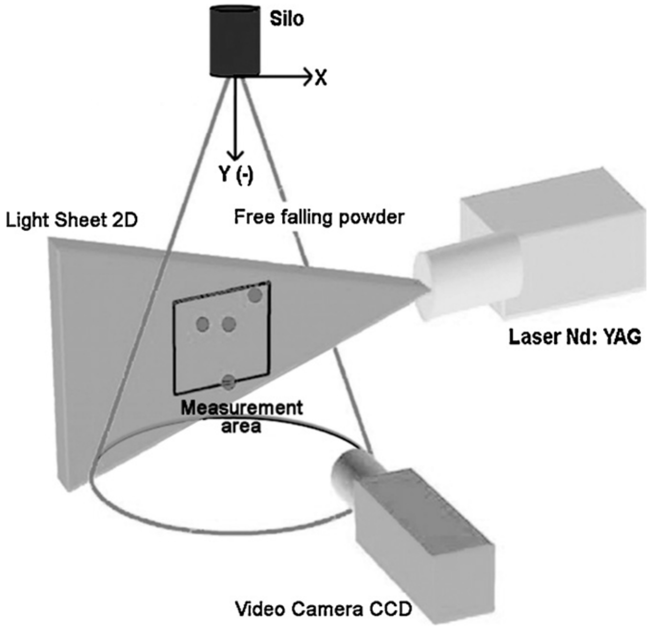

Fig. 4. PIV system.

central circular hole, which can be varied in diameter. The quantity of powder recovered from this bin is weighed. The powder weight is divided by the theoretical weight calculated from the mass flow rate obtained by the mass sensor. This allows calculating a mean mass fraction of particles falling through each orifice diameter. This method is quite intrusive and the precision of the measurements depends on the ratio between the area of the hole in the plate and the cross section of the plume.

The second measurement enables us to determine the volume flow rate of entrained air. In the process of free fall, the particle plume passes through the orifice into the bottom part of the box where a pressure sensor (Honeywell DCAL405DN with a maximum pressure variation of 1245 Pa and a total error of ±1%) is used to measure the air pressure between the bottom part of the box and the outside ambient air. An air pump is used to extract air from the vents of this region with a flow rate adjusted to maintain a zero static pressure difference between the inside of the box and the outside ambient air. The quantity of air exhausted measured by a gas meter is equal to the sum of the volume flow rate of powder and the entrained air. By using lids with various diameter orifices the volumetric flow profile in the jet can be obtained for the different sized openings (Fig. 2). The accuracy of the methodology chosen has been previously checked and validated [6]. This experimental methodology adopted by Cooper follows the approach of Ricou and Spalding [7], who studied the phenomenon of entrainment in air jets. Cooper assumed that the shelf did not make a significant difference to the volumetric flow rate observed through the opening as compared to the same situation without the orifice in place.

The powder used in this study is a silica gel with a particle density $\rho_p = 1000\,\mathrm{kg\,m^{-3}}$and a loose poured bulk density $\rho_b = 535\,\mathrm{kg\,m^{-3}}$. The particle size (determined by the Mastersizer 2000 with 0.5 bar of dispersion) is $d_{10} = 34\,\mu\mathrm{m}$, $d_{50} = 60\,\mu$ m and $d_{90} = 97\,\mu\mathrm{m}$. In this study, the silo outlet diameters used were $D_0 = 10$ mm generating a mass flow rate of $Q_{m0} = 1.5\,\mathrm{g\,s^{-1}}$ for the optical measurement by using the Spraytec and PIV system, and $D_0 = 20$ mm generating a mass flow rate of $Q_{m0} = 15\,\mathrm{g\,s^{-1}}$ for the mass concentration and air entrainment measurements. A low mass flow rate is used for optical measurement in order to have a dilute flow and have a good light transmission for the Spraytec.

3. Results and discussion

3.1. Migration of fine particles in the falling jet

The results of the particle size distribution obtained by the Spraytec are presented in Fig. 5. The size distributions are measured at $h = 87$ cm from the hopper outlet for different radial distances. It was impossible to obtain measurements at the centre of the stream since the plume is too much concentrated. The size distribution is represented by the d_{10}, d_{50} and d_{90} diameters. We observe that the value of the particle sizes in the core agree well with the measures obtained by the Mastersizer 2000. Above a radius of around 12 times the outlet diameter ($r = 6$ cm), we note that the d_{90} is reduced by about 35% from the centre of the stream to its edge, although the d_{10} is only reduced by about 15%. This indicates a segregation of the fine particles, which are blown out from the core of particles to the “dust boundary layer”. Furthermore, these size distribution experiments allow the definition of a core, where the size distribution remains constant, and a boundary zone showing that the core zone expands with a spread angle of $\alpha = 100 \times (6 - 0.5)/87 = 6.3\%$, where 0.5 cm corresponds to the radius of the outlet.

In addition, the Spraytec gives a measurement of the volume mean particle concentration at the beam patch inside the plume. This concentration is estimated by the software according to Beer–Lambert law. Unfortunately, this concentration data are not absolute values but only relative. Fig. 6 shows that maximum of the concentration at the centre is equal to 0.03%, which seems to be excessively low. This figure shows the evolution of the relative volume mean particle concentration in the jet as a function of the jet radius. The concentration, in the dusty plume, decreases from the centre to the boundary by a ratio of 6 for the same distance $h = 87$ cm.

The PIV system can be used to determine the mean velocity field of the particles in the plume for different drop heights. Fig. 7, which presents the mean horizontal velocities of the particles versus the distance from the centre, confirms that the particles move from the centre of the jet to the edge. Actually, the particles on the right side of the axe have a positive horizontal velocity and on the left side have a negative velocity. This migration velocity is important in the expansion zone and decreases thereafter. The slope of this curve decreases with the increase in the drop height. This indicates that the horizontal migration decreases with the height of fall corresponding to the flattening and uniformisation of the particle plume.

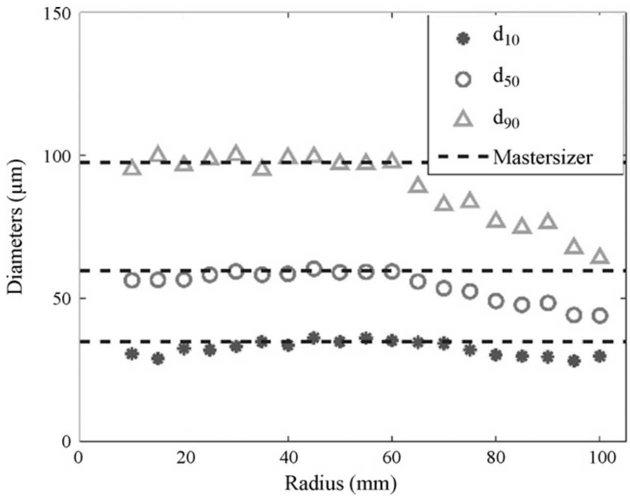

Fig. 5. Radial particle size profile in a section $h = 870$ mm (Spraytec).

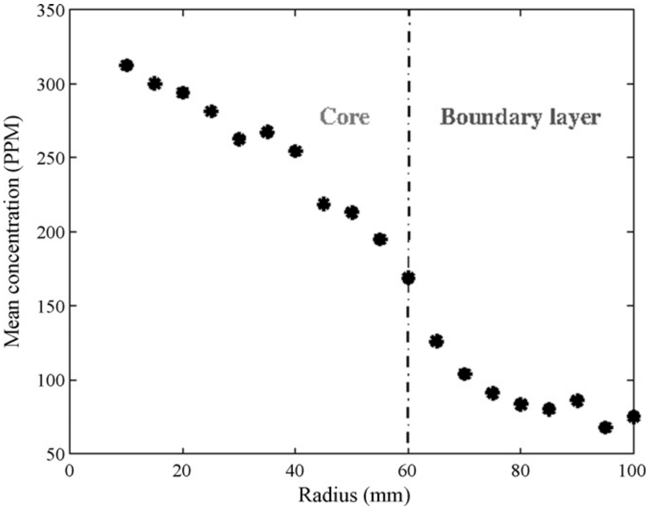

Fig. 6. Radial mean concentration in a section $h = 870$ mm (Spraytec).

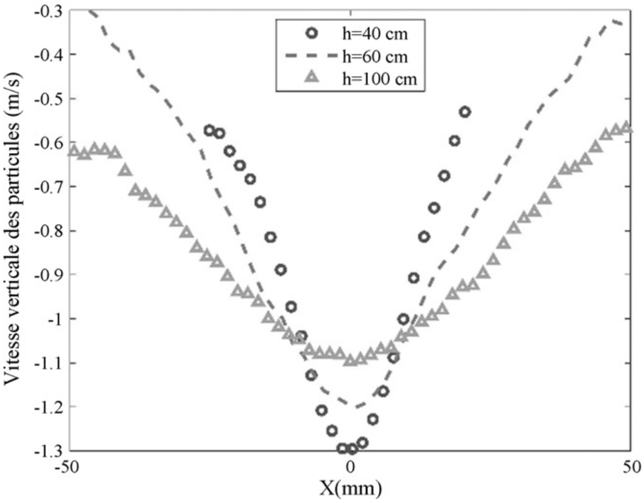

Fig. 8. Vertical particle velocity.

We can also obtain the vertical velocity profiles of the particles (Fig. 8) from the velocity field. In the plume expansion zone, as the particle concentration profiles, the vertical velocity profile has the shape of a Gaussian curve. The core region has higher velocity than the dust “boundary layer” region which has the smaller particles. The width of this Gaussian bell curve increases with the drop height while the maximum velocity at the centre decreases. This evolution result agrees with typical velocity profiles obtained in jet flows: the moving layers of the fluid experience friction with the nearby stagnant fluid. This friction originates movement of the adjacent layers which causes the spread of the jet. The spread of the jet causes the reduction of the mean bulk density. The reduction of the bulk density causes a reduction of the intensity of the motion force of the plume particles, which is dependant on the difference between the bulk density and the air density, and finally the reduction of the particle velocity. The evolution of particle velocity is due to the reduction of the particle volume fraction with increasing drop height. When the particle volume fraction decreases, the air friction on each particle increases which leads to reduced particle velocity.

The diffusion of the jet is proportional to the distance from the orifice. So, we can define a spread angle of the plume which is given by calculating a half width where the axial particle velocity is half of the centre-line particle velocity (Fig. 8). For the case studied here this spread angle is equal to $\alpha = 6\%$ which is very close to the measurements obtained with the Spraytec.

3.2. Particle mass fraction

The results obtained by weighing are shown in Fig. 9 as a function of the radial position for three different drop heights. It can be seen that the mean mass fraction increases when the orifice plate diameter is increased. Moreover, the diameter required to catch the particles emitted increases with increasing drop heights. In fact, the particle mass radial fraction gradient decreases with increasing drop height.

These measurements enable us to propose a schematic representation of the plume expansion (Fig. 10). The slope of the spread of the plume has been calculated by a linear fit for each mean mass fraction. Fig. 10 shows the jet expansion between a drop height ranging from 50 cm to 1 m. It is noteworthy that the slope of 6.3% obtained by the Spraytec corresponds to a mass fraction of 83%. Outside this cone, 17% of the powder mass emitted from the silo becomes dust. Moreover, we can note that the origin of this cone is not at the outlet as we would expect. In fact the jet contracts immediately after exiting from the hopper outlet (Fig. 3) and thereafter maintains an approximately constant radius for a con-

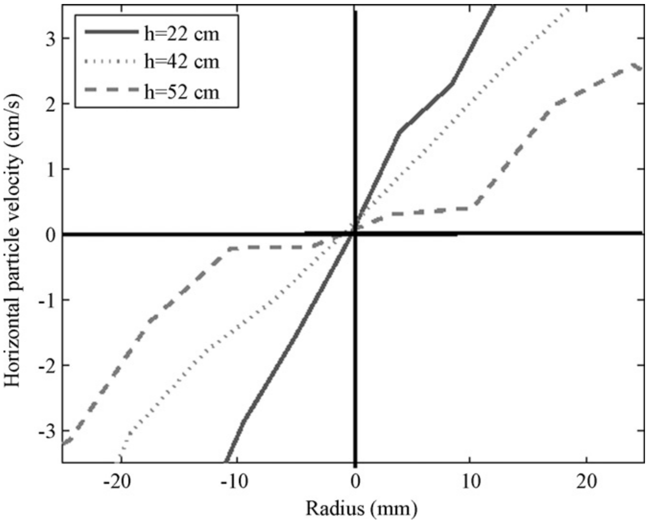

Fig. 7. Horizontal particle velocity.

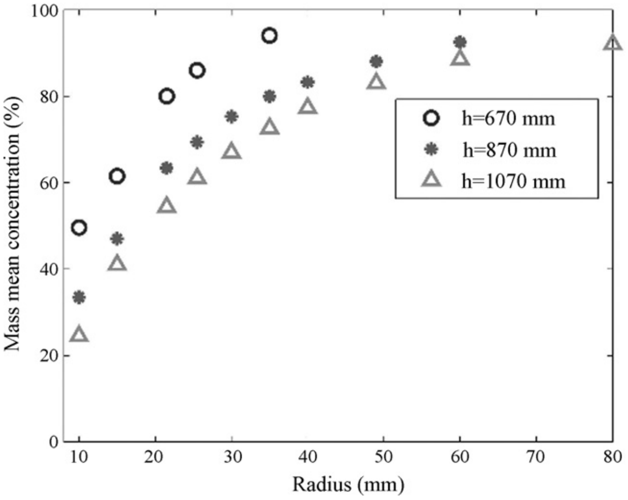

Fig. 9. Particle mass fraction.

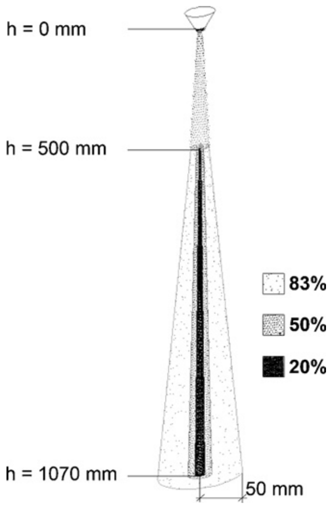

Fig. 10. Schematic of plume spread between 50 cm and 1 m.

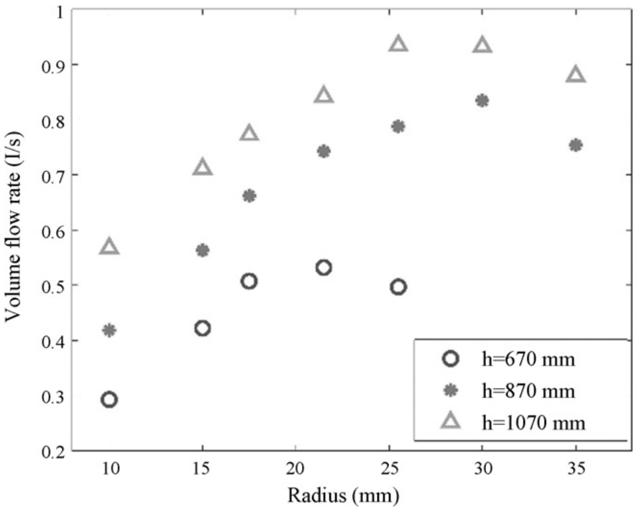

Fig. 11. Volume flow rate of entrained air.

siderable height before expanding later. This contraction can be attributed to the lower pressure created by the particle velocity increasing just after the outlet and the slope of the hopper converging.

3.3. *Spread of the plume*

We used three different methods to determine the spread angle α of the plume: particle velocity measurements, radial particle size distribution and mass concentration. All these methods lead to almost the same angle. In a previous paper [5], we demonstrated that this angle is dependant on fine particles content of the powder. Using these results in Liu's model [4], which is strongly dependant on the spread angle, we can obtain a good prediction of the particle velocity and the volume flow rate of air entrained into the plume. Moreover, in the same paper, we have observed that the spread angle varies with the particle size distribution. This angle increases with the decrease of the particle size.

The dustiness of a powder is not just an inherent property of a powder as it depends on the way the powder is stressed. As explained, an important case of dust emission is when powder is in free fall. Thus, the determination of the spread angle may be a useful way to characterise the dustiness of powder.

3.4. *Air entrainment by the falling stream of powder*

Recent research carried out by Cooper and co-workers [8] indicated that the volume of entrained air was found to be proportional to the drop height. The air entrainment per unit mass of parent bulk material (Q_v/Q_m) was also found to decrease with increasing mass flow rate of solid.

The aim of this present study is to determine the dust volume concentration in the contaminated air. To achieve this, we have performed the same kind of air entrainment measurements as made by Cooper and co-workers [8]. The observations described above of the mass mean concentration obtained by weighing allow us to get the volume flow rate of entrainment air (Q_v), which is the volume flow rate of bulk material (Q_{vp}) minus the volume flow rate of powder ($Q_v = Q_{vp} - Q_m/\rho_p$).

The results for the volume flow rate of extracted air are shown in Fig. 11 as a function of distance from the centre of a spray for different heights. As shown by Cooper in his experiments, the volume flow rate increases with increasing drop height. It may also be noted that the volume flow rate of entrained air increases with increasing orifice diameter up to a critical diameter, after which it starts to decrease. Just at this critical diameter, the plume is not concentrated enough to prevent the over-pressure generated. Thus, the kind of measurement used here is only relevant at the centre of the jet, where the plume has a high concentration.

At the centre of the plume, the ratio between the mass flow rate per particle density, and volumetric flow rate of bulk material enables us to define particle volume fraction:

$$\phi = \frac{Q_m}{\rho_p Q_{vp}} \tag{1}$$

Unfortunately, we cannot estimate the particle volume fraction over a horizontal section because, as discussed previously, the volume flow rate measurement is only relevant at the centre. Thus, to obtain the radial profile of particle volume fraction, we have combined the absolute measurement made at the centre of the plume to the relative evolution of Gaussian profile of the mean concentrations as determined with the Spraytec.

Fig. 12 presents the radial profile of the particle fraction simulation for three drop heights. The particle fraction of the plume decreases with drop height as the fine particles break away from the core to feed the dust "boundary layer". An issue of particular interest is the evolution of slope of the profile with increasing drop heights. It is found that the slope of the curve tends to zero with increase

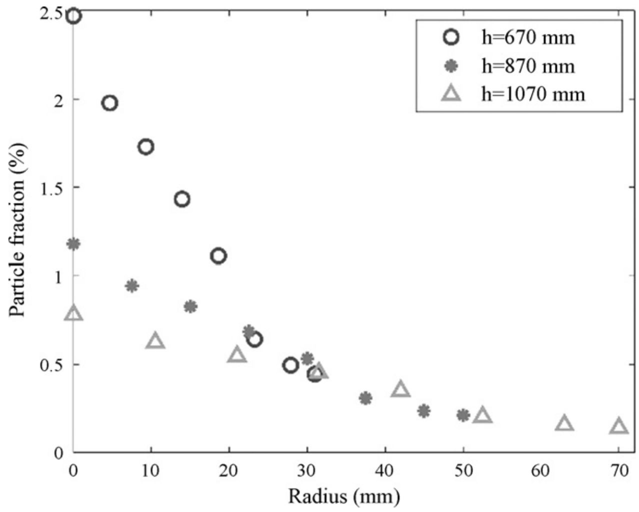

Fig. 12. Particle volume fraction.

in the drop height leading to an almost homogeneous air/particles mixture.

4. Conclusion

In order to better quantify the amount of dust which may be emitted from a vertical particle flow, we have improved the Cooper experiments based on measuring entrained air, by measuring the particle concentration, particle size distribution, and the particle velocity inside the flow. This allows us to obtain the first values for dust volume concentration inside the boundary layer surrounding a particle jet, which is the first step for estimating the rate of emission of dust. We have also demonstrated the segregation of the fine particles in this boundary layer and obtained the concentration profile in the core. Such information should be useful for developing more reliable design procedure for dealing with dust emission in powder handling operations.

Furthermore, we have determined the spread angle of the plume with three different methods. This angle is necessary to predict the particles velocity and the quantity of air entrained into the plume. Concerning the characterisation of the dustiness of powders. It may be suggested that the spread angle α could be used to compare two powders in a more fundamental way than offered by conventional empirical dustiness tests.

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