PAPER • OPEN ACCESS

Experimental measurement for non-spherical bulk materials flow behaviour in rectangular enclosure

To cite this article: Anis Farhanah Mohd Fadzir *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **701** 012061

View the article online for updates and enhancements.

Experimental measurement for non-spherical bulk materials flow behaviour in rectangular enclosure

Anis Farhanah Mohd Fadzir[1], *Siti Ilyani* Rani[1,*], *Jolius* Gimbun[2]

[1]Faculty of Chemical Engineering Technology, TATI University College, 24000, Malaysia
[2]Center of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang, 26300, Malaysia.

Abstract. Dust control is a major concern in food industries since dust emission is generally unavoidable during bulk material handling. Obtaining a better understanding of the way particles are pulled away from a stream of particles and the generation of a dust cloud will assist in the design of more efficient dust control systems. In this paper, the particles-air interactions during free fall of bulk powder is reviewed. An experimental investigation was performed to elucidate the effect of conveying velocity and particle properties on velocity profiles. The Laser Doppler Anemometry (LDA) technique was employed to measure the particle velocity during free fall. Results revealed that the particle properties (particles with flaky shapes and lower bulk density) had a great influence on dust cloud generation as compared to the conveying velocity. The results presented here may facilitate the development of a quantitative tools for dust control system design that deal with a falling stream of bulk powder.

1 Introduction

The transportation of bulk powder is a vital process in food industries since numerous raw materials and products are in powdered or particulate form. Operation involving particle handling and processing, airborne dust may arise from the dispersal of powder and could cause air pollution, contaminate industrial buildings which may affect the employee health and can trigger an explosion. In operation involving free falling of bulk materials such as in silo, a dust cloud can be formed since some of the particles are broken away from the particle stream to the surrounding air, and hence form the first airborne dust. Continuous airborne dust may be generated due to the re-suspension and re-dispersion of smaller particles that rebounded away from the particle stream during the impact of a free falling stream onto a surface. Figure 1 illustrates the dust generation for a free falling stream of bulk materials.

* Corresponding author: ilyani@tatiuc.edu.my
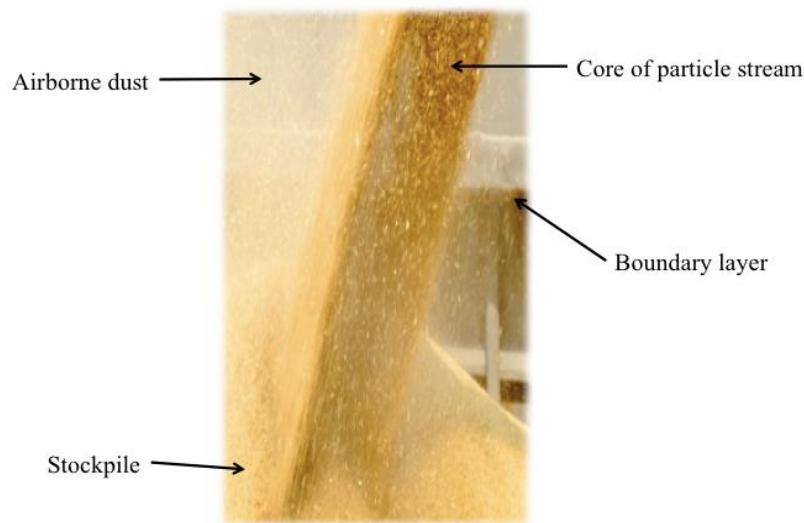
Fig. 1. Dust generation for a falling stream of bulk materials.

Understanding about the mechanism of particle settling is important to elucidate the dust generation during free falling, and hence assist in the design of effective dust control systems and risk assessment. Numerous studies have attempted to explain the motion of the particle stream based on spherical particle [1-3]. In 1995, Cooper and Arnold [4] found that dust cloud generation was due to the dust released from the impact onto stockpile. Ogata [5] reported that the free falling velocity of a single particle in an unbounded fluid was lower than a particle in a powder jet and the velocity increased with an increasing mass flow rate. The study by Wypych et al. [6] examined the air entrainment of a free falling bulk materials. In 2009, Ansart et al. [7] studied the dispersity of free falling particles with a particle image velocimetry (PIV) camera and their analysis had attempted to explain important theories and experimental significant on gas–solid flows, air entrainment models and dust control. Li et al. [8] carried out a numerical study of the effects of the conveyor chute on air entrainment. Numerical investigation of dust cloud generation during silo filling by using Computational Fluid Dynamics (CFD) provides deep insights of particle/air dynamics [9-11]. A considerable amount of literature was published on air entrainment in free falling bulk materials. The development studies of air entrained by falling bulk material were traced by [12].

Although there were many research about the motion of free falling single spherical particles in an ambient fluid, air entrainment in free falling bulk materials and settling of a spherical particle stream, only a few of them focused on the motion of non-spherical particles in the particle stream during free falling. Therefore, this study aims to experimentally investigate the effect of particle properties by means of shape, bulk density and size on velocity profile during free falling. The study also explores the influence of conveying velocity on the particle motion. The study findings are beneficial to the general understanding about dust cloud formation process; hence, assist in dust control and risk assessment in industrial processes.

2 Methodology

The experimental set-up is comprised of a square Perspex test enclosure of 60 cm by 60 cm cross section and a height of 100 cm as shown in Figure 2(a). For the experiments, materials were loaded into a hopper with a square opening outlet of 65°, then discharged into an enclosure by a screw conveyor positioned under it. Different conveying velocities were used (0.9 m/s, 1.5 m/s and 2 m/s) to produce different mass flow rates of powder. The experimental method used in this test was based on the assumption that the mass of bulk material was maintained approximately constant for each powder. For each experiment, the free falling stream of particles falls into the enclosure that was prefilled with white, dense, non-irritant, non-flammable and non-hazardous fog for particle tracing. Figure 2 (b) shows the enclosure with five various vertical positions and the axial direction for measurement.

(a)   (b)
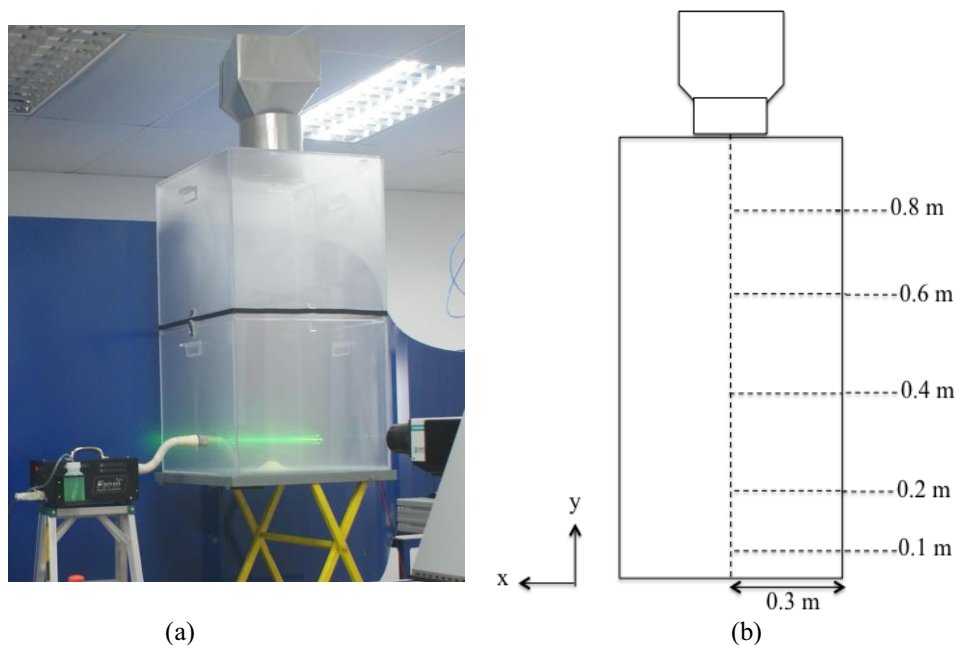
Fig. 2. (a) Experimental arrangement (b) Various positions at the enclosure for measurement.

The experimental testing for this study utilised the Laser Doppler Anemometry (LDA) to measure the velocity profiles of particles in the particle stream. The calibration was undertaken prior to commencement of measurement to ensure the continuous laser was specifically focused at the required point. In this setup, two 100 mW of DopplerLite diode-pumped solid-state (DPSS) laser were used with 491 nm and 514 nm wavelengths. The laser beam was divided by a Brag Cell to obtain two subdivision beams that cross outside the sensor. The crossing area was known as the probe volume. The two parallel subdivision beams were focused by a lens that intersected at a point in the falling particle stream flow, forming interference fringes. Since the particle stream flow traversed the intersection volume, the FiberLite receiving optics received light scattered from both beams that produced light intensity fluctuations. The photomultiplier converted the light intensity fluctuations to the electrical signals, which were then converted to the velocity information in the Burst Spectrum Analyser (BSA) processor. The processing results were conducted by using BSA Flow Software. This LDA system is comprised of a fully automated traverse system for positioning the optical system at different levels, as depicted in Figure 2 (b).

The materials used in the experiment are summarised in Table 1, and were selected as they have different particle shapes in nature. These materials were selected to classify the effect of particle shape on the velocity profile of a particle stream. The morphology of dust is given in Figure 3, which were taken by scanning electron microscope (SEM).

Table 1. Summary of materials.

Material	Shape	Average particle size (μm)	Bulk density (kg/m^3)
Castor Sugar	Crystal	336.3	891.2
Oat	Flaky	423.4	273.0
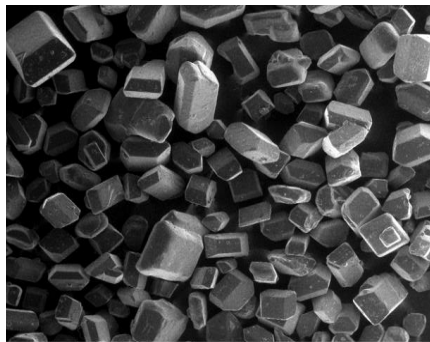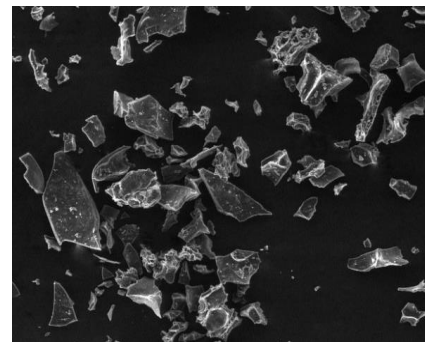
(a)   (b)

Fig. 3. Photos of dust taken with a scanning electron microscope. (a) Castor sugar (b) Oat

3 Results and Discussion

Mean velocity of particles during free fall provides an important information on structures of particle streams and dust migration. In this study, the main influence factors on the dust cloud generation, such as the particle characteristics (shape, average particle size as well as bulk density) and conveying velocity, were experimentally investigated.

3.1 Influence of Particle Properties

The schematic diagram of particle streams during free fall is illustrated in Figure 4. The drag force acting on a single particle in the particle stream is not that significant on a single particle in stagnant air. However, free falling of particles may induce downward flow of air and hence may affect the particle drag and dispersion. The free fall drag force acting on the particle is affected by the air velocity and shape of the particle. Generally, drag acting on a spherical particle is mostly uniform, but there is a high tendency of nonuniform drag force on flaky particles. The drag forces acting on falling particles are influenced by the inter-particle distance within the particle cloud. During particle falling, the inter-particle distance is very small. Therefore, very little drag force acts on the majority of particles as compared to the drag force on the exterior sides of particle flow.
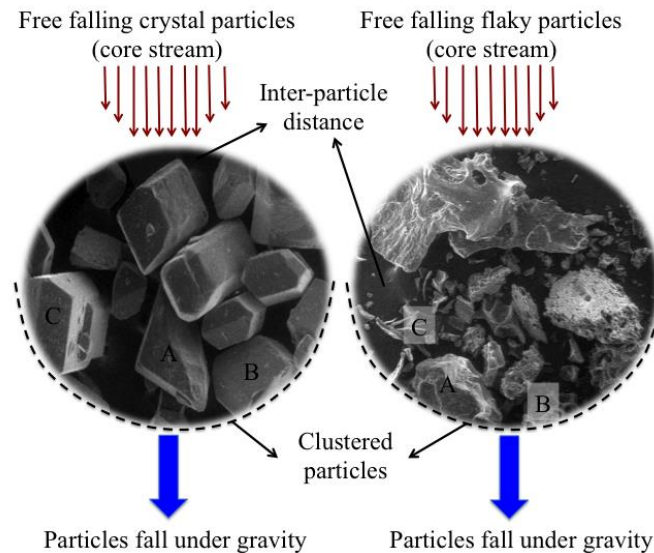
Fig. 4. Illustration of clustered particles of castor sugar (crystal) and oat (flaky) in the core stream.

The air flow pattern around a single particle is contorted by the moving clustered particles. The air flow pattern around Particle A on the left side can be gradually developed in the opposite direction of the particle movement, generating turbulent wakes, which will modify the turbulence of air. Hence, the pressure on the left side of Particle A will gradually decrease. However, the air flow pattern on the right side of Particle A, may not be well developed due to the influence of Particle B. Therefore, the drag force on the left side of Particle A is larger than that on the right side, which may possess a tendency of clockwise rotation. The drag forces on Particle A are different than those of Particle B due to its shape and size. With further downstream, the particle flow begins to break up into smaller clusters, which increase the exposure of the powder into the air. Once the drag force achieved a certain value, Particle A will be pulled away from the stream core of the stream and escape into the surrounding to become an airborne dust.

Assuming the same phenomenon, the uneven drag forces will cause Particle C to be pulled away from the core of the stream. The drag force will induce the air into the falling particle stream and the particle flow will appear to be largely broken up during free fall. Due to the motion of particle free falling, the voidage of the particle stream will increase with increasing drop height and more surrounding air will be induced into the stream core. Therefore, the particle flow increases rapidly in this regime and will cause a gradual reduction in the core stream diameter. Since the core of the particle stream disappears, forces acting upon a particle in the flow become equivalent to each other, which makes the particle velocity close to terminal velocity. Therefore, the particle movement decelerates until it stops.

3.2 Influence of Conveying Velocity

The mean velocity plotted in Figure 5 clearly shows the influence of particle properties in dust cloud generation. It was observed from Figure 5 (a) that the flow of castor sugar in the core stream increased with further downstream as a result of moving clustered castor sugar particles. Higher bulk density (891.2 kg/m^3) of castor sugar particles (in crystal shape) with

smaller voidage prevented the drag force to disrupt the particle flow. Hence, the particle flow at the core stream underwent accelerations with increasing conveying velocity. In Figure 5 (b), there is a clear trend of decreasing flow of oat particles with increasing drop height. Oat particles conveyed with 2.0 m/s decelerates at 0.1 m from the bottom of the enclosure due to the terminal velocity. Low bulk density (273.0 kg/m^3) and far inter-particle distance of oat particles (in flaky shape) are the important factors to encourage drag force action in generating a higher dust emission during free falling, regardless of particle size.

It was observed in Figure 5 that the measured mean velocities of the LDA results had significant impact on particle characteristics and showed a slight impact on conveying velocity for different enclosure positions. The mean velocity plotted in Figure 5 clearly shows that particles in the core region (centre) had a higher velocity than the dilating region (from the wall), which has smaller particles. Also, the width of the curve from 30 cm (the centre of enclosure) increases towards the bottom. The finding is consistent with findings of past studies by Ansart et al. [7], where the moving layers of the fluid experience friction with the nearby stagnant fluid. This friction initiates the movement of nearby layers, which causes the spread of particles. The spread of the particle causes a reduction in the mean bulk density. The reduction in bulk density causes a reduction in the intensity of motion force of plume particles, due to the difference between bulk density and air density, and finally the reduction in particle velocity. The development of particle velocity is due to the reduction of the particle volume fraction with increasing drop height. It was found that when the particle volume fraction decreases, the air friction on each particle increases, which leads to reduced particle velocity.

It is appears from Figure 5(a) that the increment of conveying velocity did not show any significant difference on the particle velocity in all positions, except a slight velocity difference for 0.9 m/s of conveying velocity. After comparing the trends displayed in Figure 5 (a), it can be seen that the highest conveying velocity (2.0 m/s) produced the highest downward mean velocity towards the core of particle stream. Figure 5(b) is quite revealing in several ways. The results suggested that the mean velocities at the core stream were proportional to the speed of conveying velocities at positions 0.8 m, 0.6 m and 0.4 m. However, at 0.2 m from the bottom, the mean velocity of free falling particles at 0.9 m/s and 1.5 m/s conveying velocities were decreased towards the centre due to terminal velocity. What is interesting in this data is that the mean velocity of particle conveyed by the highest conveying velocity (2.0 m/s) at the bottom of the enclosure (0.1 m), reduced about 20% from the top due to the particle-fluid interaction, such as the drag force resulting in the deceleration of particle flow.
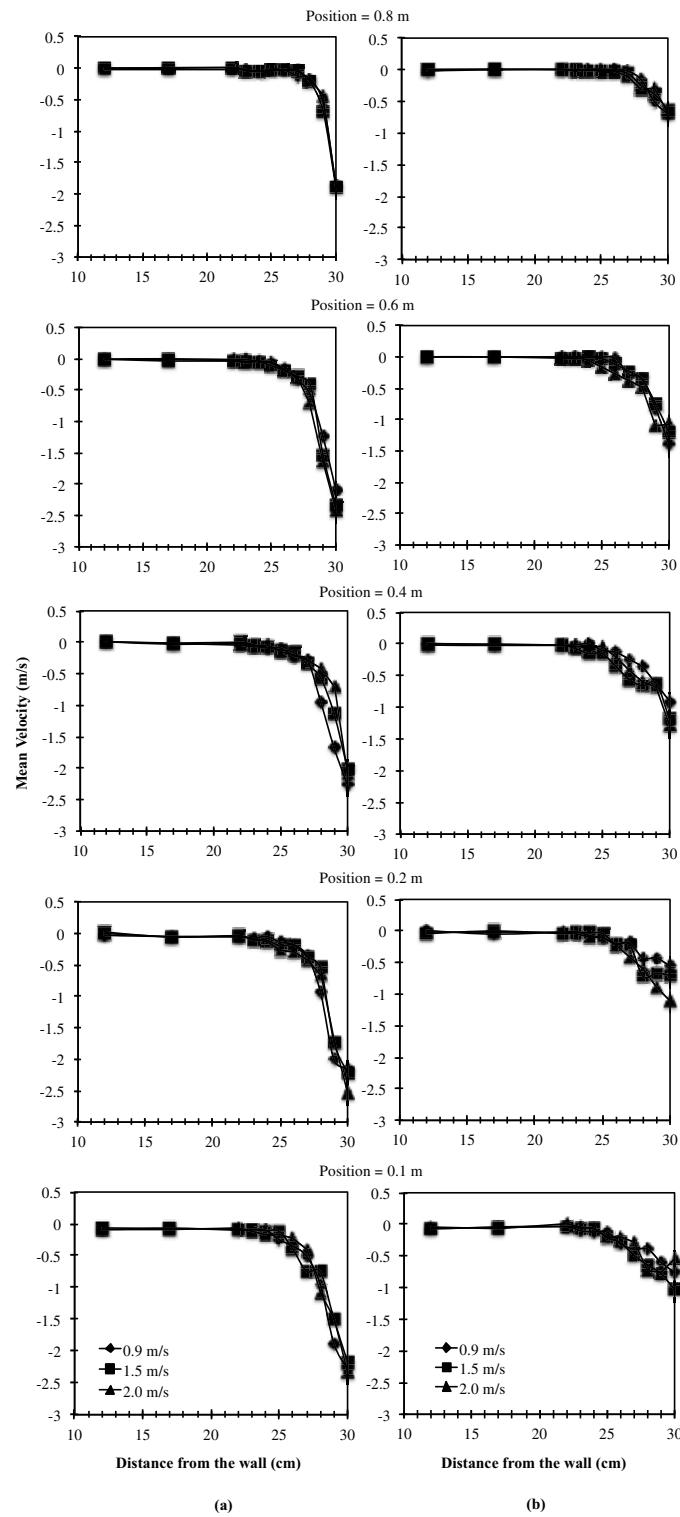
Fig. 5. Measurement of mean velocity at various positions for (a) castor sugar and (b) oat.

4 Conclusion

The effect of particle density and particle shapes on the dust cloud formation and particle velocity was elucidated using a noninvasive LDA technique. The result shows that particle shapes greatly influence the particle falling velocity. Oat particle which has a flaky shape has about 60% less free falling velocity compared to castor sugar which is mostly in smooth cube shape. The flaky particles also tend to generate a larger dust cloud due to non-uniform draf forces acting on the particle surface.

References

1. M. Crawford, *Air pollution control theory* (McGraw-Hill Book Company, New York, 1976)
2. G. Gouesbet, A. Berlemont, Prog. in Energy and Combustion Sci. **25**,133–159 (1999)
3. A.A Esmaili, T.J. Donohue, C.A. Wheeler, W.M. McBride, A.W Roberts, I. J. of Mineral Processing **142**, 82-90 (2015)
4. P. Cooper, P.C. Arnold, Kona Powder Part. J. **13**, 125 (1995)
5. K. Ogata, K. Funatsu, Y. Tomita, Powder Tech. **115**, 90–95 (2001)
6. P. Wypych, C. Dave, C. Paul, Chemical Eng. and Processing: Process Intensification **44**, 323–326 (2005)
7. R. Ansart, A. Ryck, J.A. Dodds, M. Roudet, D. Fabre, C. Francois, Powder Tech. **190(1-2)**, 274–281 (2009)
8. X. Li, Q. Li, D. Zhang, B. Jia, H. Luo, Y. Hu, Adv. Powder Tech. **26**, 236-243 (2015)
9. A. Klippel, M. Schmidt, O. Muecke, U. Krause, J. of Loss Prevention in the Process Industries **29**, 22-137 (2014)
10. S.I. Rani, B.A Aziz, J. Gimbun, Process Safety and Env. Protection **96**, 14-21 (2015)
11. L.L.L. Waduge, S. Zigan, L.E. Stone, A. Belaidi, P. García-Trinanes, Process Safety and Env. Protection **105**, 262-273 (2017)
12. X. Li, Q. Wang, Q. Liu, Y. Hu, Powder Tech. **291**,159-169 (2016)