Hydrodynamic Behavior of Particles in a Jet Flow of a Gas Fluidized Bed

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ABSTRACT: *Numerous investigations have been devoted towards understanding the hydrodynamics of gas jets in fluidized beds. However, most of them address the problem from macroscopic point of view, which does not reveal the true behavior in the jet region at the single particle level. The present work aims to understand the jet behavior from a more fundamental level, i.e. the individual particle level. A thin rectangular gas fluidized bed, constructed from acrylic glass, with a vertical jet nozzle located at the centre of the distributor was used in the work. A high speed camera with a speed up to 10,000 frames per second was used to observe the jet behavior. Analysis of large quantity of images allowed determination of solids flux, solids Velocity and solids concentration in the jet region. The model present in this work has shown better agreement with the experimental data in compare with the previous models presented in the literature.*

KEY WORDS: *Gas fluidization, Jet, Particle velocity, Solids flux, Particle concentration.*

INTRODUCTION

Fluidized beds with jets have found applications in many industrial processes to involving drying, granulation, coating, and strong endothermic/exothermic reactions such as gasification and combustion of coal. The use of a jet can increase the overall solids circulation and hence enhance heat and mass transfer. How ever the use of jet, can also lead to serious attrition and breakage of particles in the bed. A fundamental understanding of the jet behavior and its interaction with the bulk bed is therefore important for both process design and system operation. Due to their industrial importance, fluidized beds with a single jet or multiple jets have been the subject of many experimental and theoretical investigations. These studies can be broadly divided into those on beds with a single jet and those on beds with multiple-jet [1-3]. These two categories could then be subdivided according to jet orientation: vertical jets located in or near the main gas distributor [3-9] and horizontal jets situated at the side of the bed [5, 8, 10]. These studies have focused mostly on the macroscopic behavior of the jet, e.g. jet penetration height, which has an important bearing on the mixing and heat and mass

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transfer inside the bed.

However these studies, paid little attention to the solids behavior inside the jet, which may exert important influence on particle attrition as mentioned above. This provides the Motivation of a systematic investigation into the solids behavior in the jet region of gas fluidized beds. This paper reports a recent experimental study on the behavior of a vertical jet introduce into a pseudo two-dimensional fluidized bed. The focus is on the solids behavior, in particular, velocity and concentration profiles in the jet region, and solids exchange between the jet and bulk bed regions. This paper is organized in the following manner: The experimental technique will be described in Section 2, whereas the experimental results will be presented and discussed in Section 3. Finally, conclusions will be summarized in Section 4. References of relevant work reported in the literature will be made where is appropriate.

EXPERIMENTAL TECHNIQUES

Various techniques have been employed to study the behavior of gas fluidized beds. Examples include cinematography and direct photography [11-13], X-ray based techniques [14,15], ©-ay and radioactive tracer based techniques [16-18], laser Doppler anemometry (LDA) [19], optic fibre probes [20], and electrical capacitance tomography [21]. The cinematography and direct photography techniques are obviously applicable only for studying pseudo two-dimensional fluidized beds and their capabilities are very much dependent on the speed in terms of frames per second, shutter speed, and the spatial resolution. Despite their limitations, the cinematography and direct photography are among the most frequently used methods in studying gas fluidization behavior. For example, they have been employed in measuring voidage profiles in spouted beds [11], particle velocity in fluidised beds [12,13], bubble dynamics, mixing and segregation [22-25], and bed expansion [26,27].

This work employs a high-speed video camera coupled with image analysis software. The camera has a frame frequency of up to 10,000 frame per second (fps), which makes it possible to track individual particle motion. The high speed camera consisted of a Red Lake motion Xtra HG-100k camera, a data Transfer cable, a lighting unit, and an imaging PC. The camera was able to capture images at a rate of up to 10,000 fps with a resolution of 1504×1128 pixels. The imaging PC was equipped with Optimas version 6.0 software. The image analysis software make it possibleto process all the images which capture by camera and manipulates information with in an image to make it more useful, with help of this soft ware in the first step the images enhance for further clearance in recognizing the features of interest, second step is identifying the feature of interest by setting a threshold (threshold is a set of intensity values that separates pixels of interest from the rest of the image) and that makes the possibility that the feature of interest automatically identifying in the other images and in the third step the length and angle of motion, number and velocity of the features of interest measure by tracking of individual particles(features of interest) in consecutive frames.

The experimental system used in this work consisted of a narrow rectangular bed, a multi orifice distributor, a gas supply and control system, and the high speed camera. The rectangular bed was made of 'Perspex' acrylic glass, with dimensions of 0.2 m (Width) × 0.012 m (Depth) × 1.5 m (Height). A brass perforated plate with 0.5×10^{-3} m diameter holes was used as the distributor (Fig. 1). A rectangular aluminum nozzle was inserted vertically in the middle of the distributor for the introducing a jet continuously.

The nozzle outlet was flushed with the distributor, while the inlet extended to the bottom of the wind box and was connected to an independent external gas supply. The nozzle, 0.5×10^{-3} m wide and 0.012 m deep, divided the wind box into two sections each with an independent gas supply. Compressed air metered by Rota meters was used for both the fluidization and jet gas supplies.

Spherical zeolite beads were used in this work. They had a diameter of 1.9×10^{-3} m, and a bulk density of 1200 kg/m3 (Group D classification) in terms of Geldart classification. The strategic selection of relatively large but light particles allowed for more accurate tracking of individual particles.

In the experiments, particle bed had a average height of 0.17 m. The bed was maintained at the minimum fluidization state with a superficial gas velocity of ~ 0.3 m/s, while the jet velocity was varied between 70 – 115 m/s. The images were acquired at 3000 fps. Particle identification was based on the threshold colors image command by defining the threshold of the object of

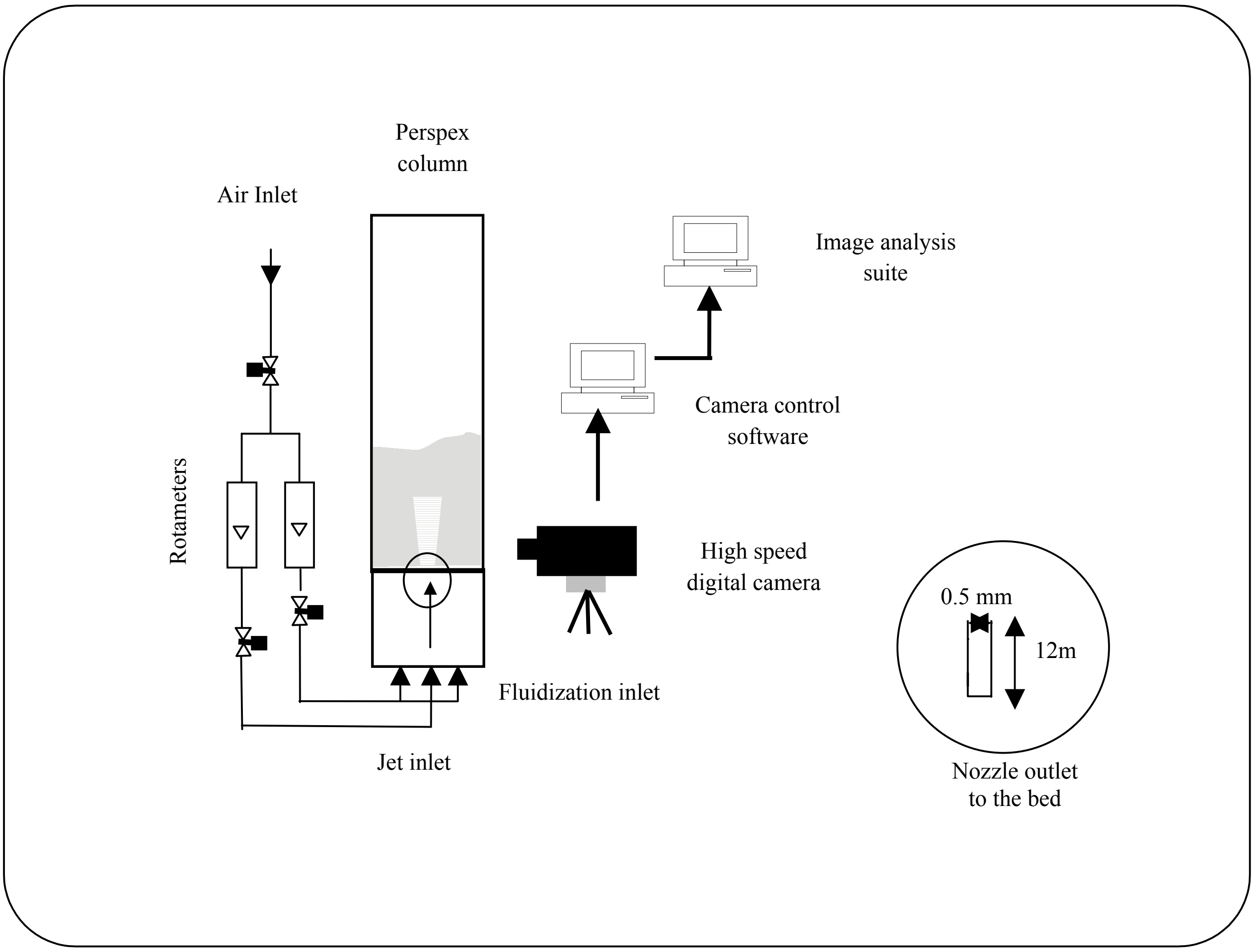


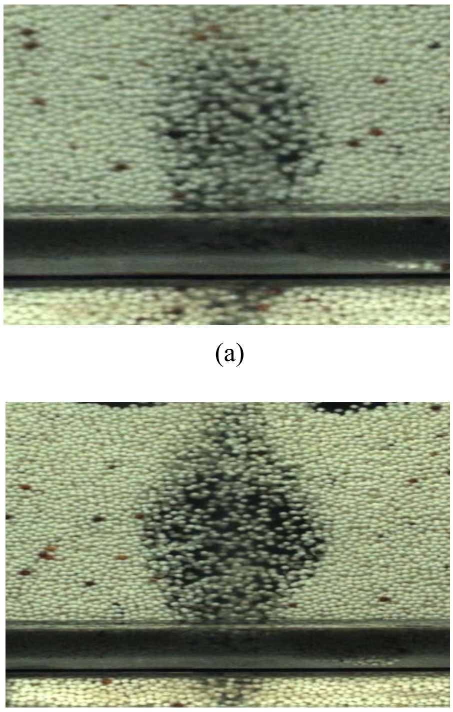
Fig. 1: Experimental Rig.

interest (particles) in one specified image and after this step the objects can be identified automatically in all the following images.

RESULTS AND DISCUSSION

General observations of solids motion in the jet region

Fig. 2 shows two typical images of the jet region created at jet velocities of 70 and 92 m/s. It can be seen that very high quality images have been obtained. Video playback shows that particles generally move into the jet region from the lower part of the jet from where they are accelerated. When particles reach a certain axial position in the jet region deceleration due to the axial momentum dissipation of gas and decrease of drag force on particles starts. Axial particle velocity then continues to decrease until the gas (jet) momentum flux is equal to back ground momentum flux at the jet boundary in the upper part of jet region where jet collapse and particles enter the bulk bed. Solids exchange between the jet and the bulk bed. Such an exchange is important to a number of applications such as coating, granulation, and particle attrition. Particles moving out of the jet region in the upper part of the jet are seen to move downwards and re-enter the jet region in the lower part of the jet. This clearly demonstrates a solids circulation pattern and hence solids exchange between the jet and the bulk bed. Such an exchange is important to a number of applications such as coating, granulation, and particle attrition. A quantitative analysis of the exchange will be made in Section 3.5. As the bulk bed was maintained at the minimum fluidisation state, solids circulation due to solids motion in the bulk bed is negligible The high quality images also allow the particle velocity and concentration to be analyzed by using the image analysis software;(Section 3.2 and 3.4, respectively).



(a)

(b)

Fig. 2: Images of jet in different gas velocity (a) Uj= 70 m/s (b) Uj= 92 m/s.

Particle velocity profiles in the jet region

Fig. 3 shows the radial distribution of the vertical particle velocity at Uj= 70, 92 and 115 m/s, where the centre of the jet nozzle is located at x = 0, i.e. the fluidized bed lies between x= - 0.1 m and 0.1 m (0.2 m width). At a given vertical position above the grid, h, particle velocity has the lowest velocity at the jet-bulk bed interface, and the highest velocity occurs at the centre of the jet. At a given gas jet entrance velocity, particle velocity decreases with jet height and reaches the minimum at the top of the jet. The results also show that particle velocity increases with increasing jet velocity as expected.

Lateral (horizontal) particle velocity profiles are shown in Fig. 4 for Uj = 70, 92, and 115 m/s. At different gas jet velocities and different vertical positions, horizontal particle velocity decreases around the central region of the bed.

Abramovich [29] first derived this profile equation (1) for two dimensional wake (based on Prandtl-Schlichting theory), and extended into free jets and submerged gas-liquid jets.

$$V / V_{max} = \left[1-(\xi)^{1.5}\right]^2 \tag{1}$$

Where Vmax is the maximum particle velocity. This equation was later shown to agree with experimental results of *De Michele et al.* [30]. However, as shown in Fig. 5 the expression (1) underestimates particle velocity in the jet region, Fig. 6 shows equation (2) provides a better fit to the experimental data.

$$V / V_{max} = \left[1-1/2(\xi)^2\right]^2 \tag{2}$$

Jet boundary region

The jet boundary is needed to calculate particle flux and concentration in the jet region. *Schlichting* [31] defined the jet boundary by considering that the lateral gas velocity is zero at the boundaries equation (3) and *Donsi et al*. [32] defined the jet boundary according to the radial particle concentration constant in the jet region and equal to the main bed concentration at boundary.

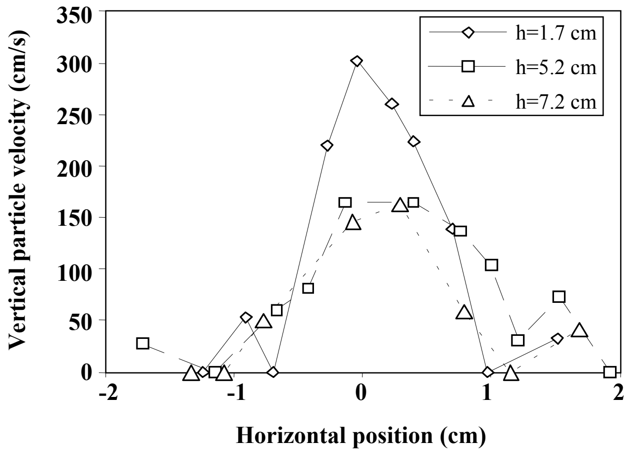
$$\frac{u_r}{u_r^*} = \frac{\xi - 1/4\xi^3}{(1+1/4\xi^2)^2} \tag{3}$$

This work looks at particle velocity once entrained into the jet. Fig. 7 shows the measured particle velocity (absolute particle velocity) profile at three different jet velocities. Particle velocity experiences a big change and happens to decrease at the boundary. Fig. 3 shows that vertical particle velocity is nearly zero at the boundary of the jet region and particles only move horizontally through the jet region and according to our work the radial distribution of vertical particle velocity V_y is equation (4).

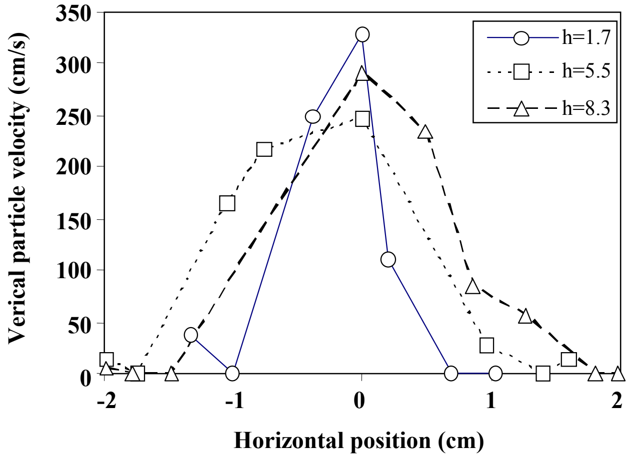
$$\frac{v_r}{v_{(max)}} = \left(\xi^2 - 1\right)^2 \tag{4}$$

Particle concentration profile

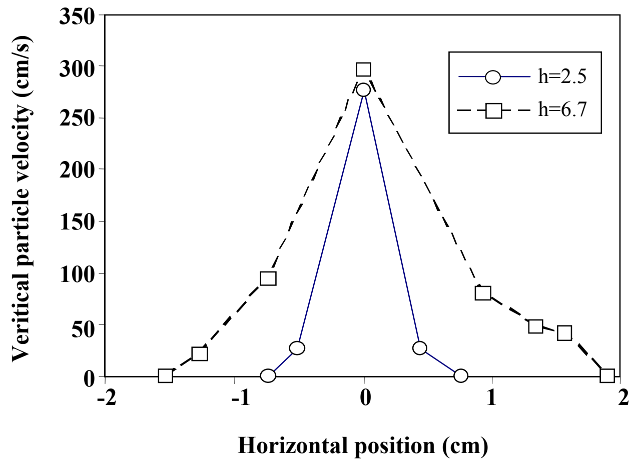
Particle concentration in the jet zone is an important parameter that determines the efficiency of the jet especially when used for agglomeration and coating processes. To determine particle concentration in the jet, images were acquired at a rate of 1000 fps, and particles were recognized automatically based on a threshold colors image by visual sampling of the area of interest. The horizontal cross-sectional area of the jet is discretized into unit area elements and particles are



(a) Velocity of gas at jet nozzle exit = 70m/s

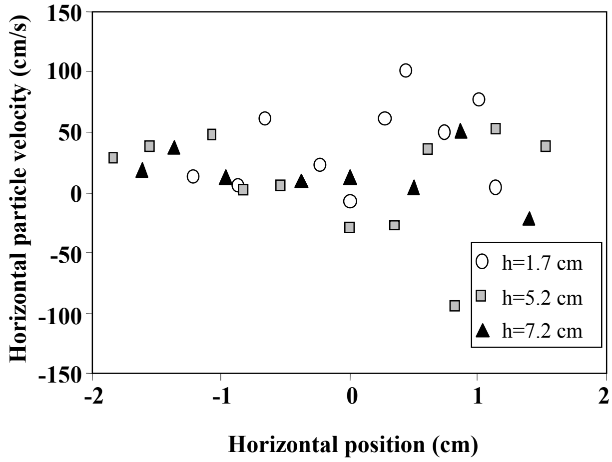


(b) Velocity of gas at jet nozzle exit = 92m/s

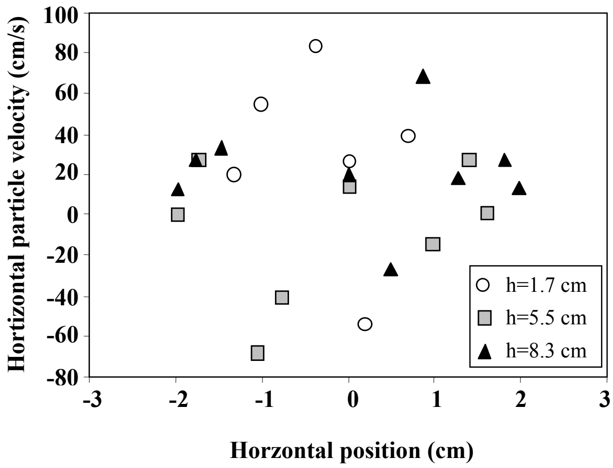


(c) Velocity of gas at jet nozzle exit = 115m/s

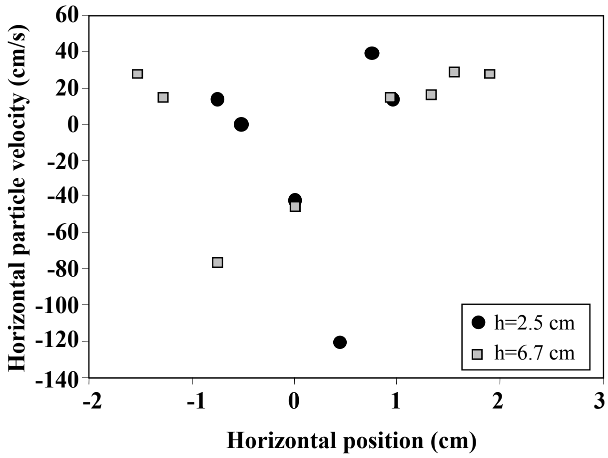
***Fig. 3:** Horizontal distribution of vertical particle velocity in the jet region.*



(a) Velocity of gas at jet nozzle exit = 70m/s



(b) Velocity of gas at jet nozzle exit = 92m/s



(c) Velocity of gas at jet nozzle exit = 115m/s

***Fig. 4:** Horizontal distribution of horizontal particle velocity in the jet region.*

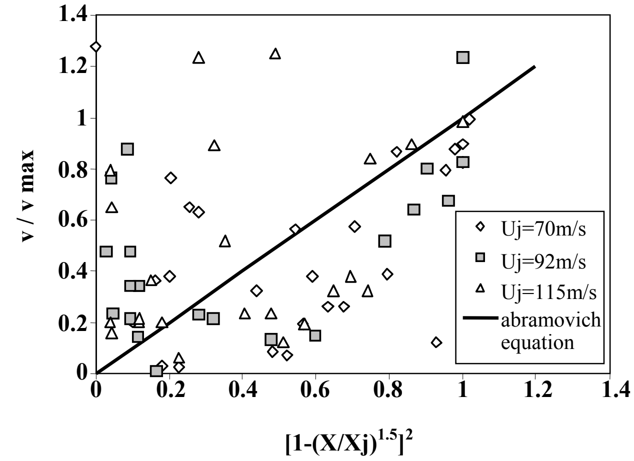


Fig. 5: Comparison between experimental data and model by Abramovich (1963).

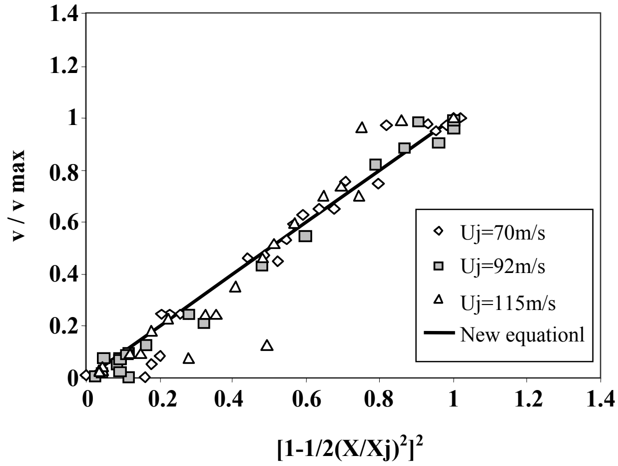


Fig. 6: comparison between experimental data and new model.

counted in each area of interest. Fig. 8 shows the lateral (horizontal) distribution of particle concentration at different gas jet velocity and different vertical position. It shows that particle concentration increases horizontally from centre of the jet to the bulk bed. At the centre of the jet, particles have the highest velocity, but with the lowest concentration. Comparison between Fig. 8 and Fig. 7 shows that particle concentration at different area of the jet linearly change with particle velocity and based on the experimental results an equation drives (5) for determination of coarse particle concentration at a specific time and at different area in the jet region.

$$1-\varepsilon = -0.25\frac{V}{V_{max}} + 0.5 \tag{5}$$

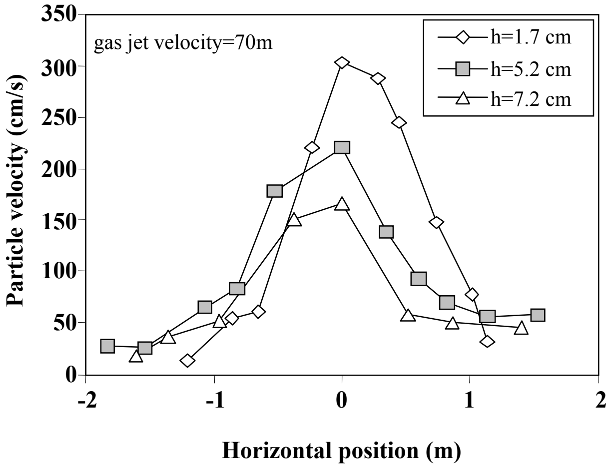
The lowest particle concentration is also seen to decrease with increasing jet velocity. Fig. 9 compares particle concentration at different vertical positions. It shows that the vertical distribution of particle concentration is less dependent on the vertical position.

Particle entrainment rate in to the jet zone

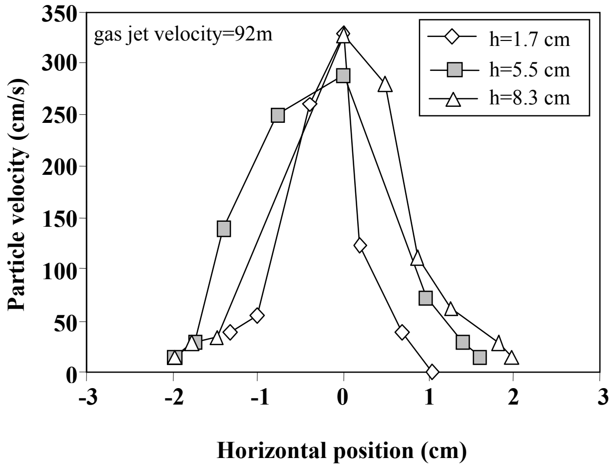
Particles moving from the bulk bed through the jet boundary are entrained into the jet region laterally. It is interesting to look at the particle entrainment rate, which is believed to be an indication of the particle circulation rate. Particle entrainment rate is expected to dependent on the average particle velocity and voidage at the jet boundary. This parameter measured experimentally by PDPA method (L.Aisa et al 2002) for particle laden jet individually not in the fluidized bed, In this work, the jet boundary was discretized into small cells and each particle situated inside a cell and the number of the frames that it takes for these particles to be entrained into the jet zone was counted and due to the mass of each particles and total number of the particles inside of the bed the mass entrainment rate calculated. Fig. 10 shows the results. It can be seen that, at a given gas velocity particle entrainment rate initially decreases with height. It then reaches a minimum at a position about 6/10 of the overall jet height, and then an increase is observed. This is due to the expansion - contraction of the jet.

Fig. 11 shows a comparison between the experimental results with that predicted using the model by *Massimilla's* [10], this model uses turbulent jet theory (*Abramovich*), [29] to describe jet characteristic and has been developed by *Donsi et al.* [32] for discharge in beds of coarse particles and solves the conservation equations for mass and momentum to obtain key parameters like solids velocity, gas velocity and solids concentration. This model defines solid entrainment rate into the jet by equation (6) and assume the jet particle velocity profile as equation (2) and also jet boundary condition, fluid and particles properties and operating condition have been defined for solving the system of equations. Good agreement has been shown between the model prediction and the experimental data.

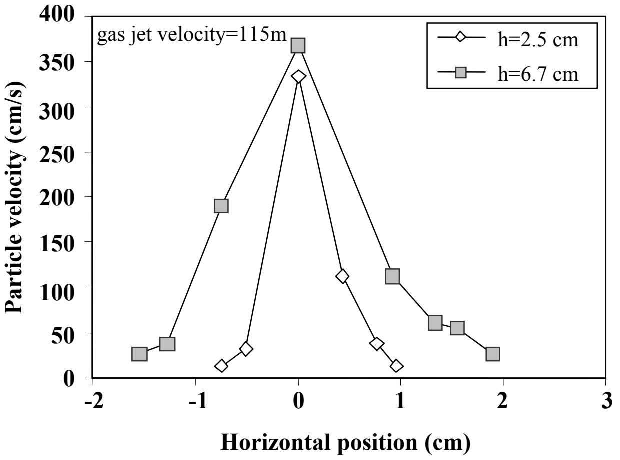
$$W_S = \pi\, b^2 \rho_s \int_0^1 V(1-\varepsilon)2\xi d\xi \tag{6}$$



(a) Velocity of gas at jet nozzle exit = 70m/s

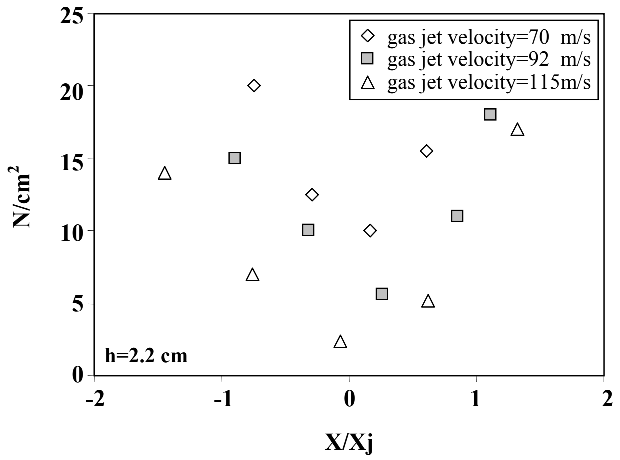


(b) Velocity of gas at jet nozzle exit = 92m/s

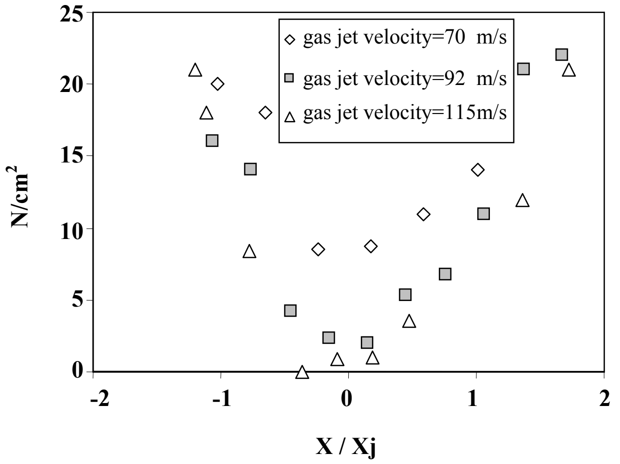


(c) Velocity of gas at jet nozzle exit = 115m/s

Fig. 7: horizontal distribution of particle velocity in the jet region.



(a) h=2.2 cm



(b) h=1/2H(jet height)

Fig. 8: Lateral distribution of particle concentration at different jet height.

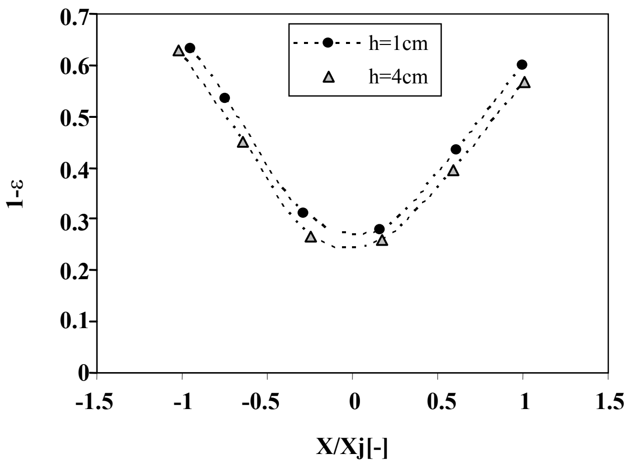


Fig. 9: Particle concentration at two different heights at 70m/s velocity of gas jet.

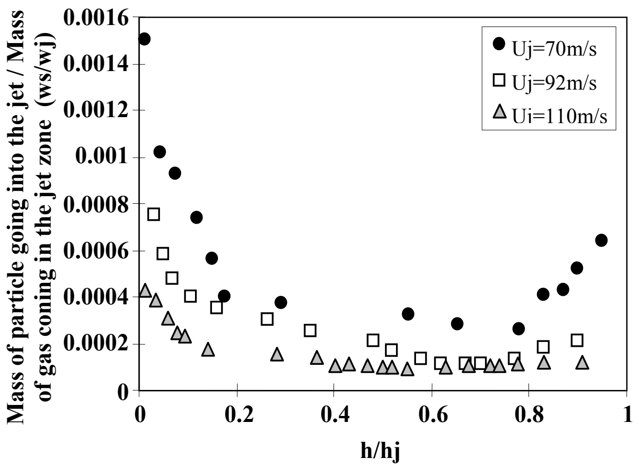


Fig. 10: Particle flux into the jet region at different gas velocities.

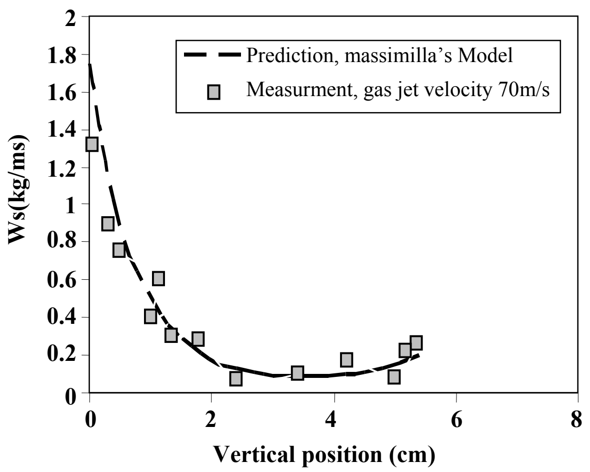


Fig. 11: Comparison between experimental data with Massimilla's model.

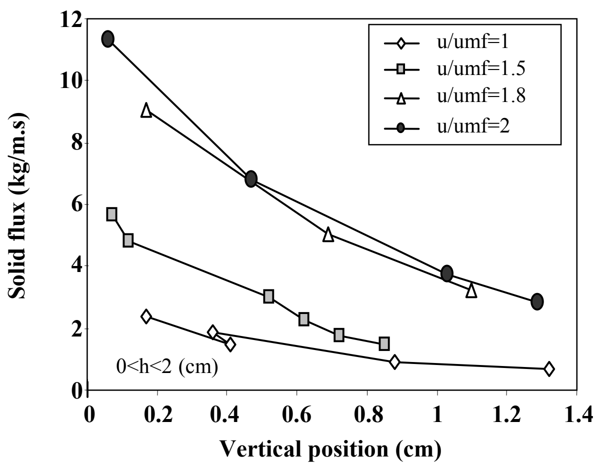


Fig. 12: comparison of particle flux into jet region at the route of the jet (0<h<2 cm) at different back ground fluidisation velocities.

Experiments were also carried out at different background fluidization velocities. Fig. 12 shows the results. The background fluidization velocity has a significant effect on the particle flux into the jet zone. At fluidization velocities higher than 2.5 Umf, fluidized bed becomes rather turbulent, which makes it impossible to measure particle flux

CONCLUSIONS

The present work uses a high-speed video camera to isolate and track temporal particle motion frame-by frame within the jet region in a thin rectangular fluidized bed with an aim to characterize the hydrodynamic behavior of the system. The dynamics of individual particles are analyzed within the jet region to map the velocity profile using equation (2) and identify the jet boundary. The result shows the distribution of particle velocity and defines the exact boundaries of the jet based on the individual particle velocity. This work also describes a new method for measuring particle flux and concentration and the experimental results determined by this method are validated by a hydrodynamic model, given in equation (6), of the fluidized Bed jet.

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Notations

b	jetting region or jet half amplitude,(m)
h j	jet vertical position,(m)
h	jet height,(m)
N	number of particles in unit area
N j	number of particle going in to the jet in different vertical position
N t	total number of particle in the bed
r(X)	jet radial position,(m)
rj(Xj)	jet radius, (m)
Uj	gas jet superficial velocity, (m/s)
U	superficial fluidisation velocity, (m/s)
Umf	minimum fluidisation velocity, (m/s)
ur	Horizontal gas velocity, (m/s)
V	particle velocity, (m/s)
Vmax	maximum particle velocity, (m/s)

V r Horizontal particle velocity, (m/s)
V y Vertical particle velocity, (m/s)
Ws particle entrainment Rate at different vertical position, (kg/s)

Greek letters

ρ_s Particle density, (kg/m^3)
ε bed voidage
ζ (r/rj) Radial dimensionless coordinate

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REFERENCES

[1] Basov, V. A., Markhevka, V. I., Melik-Akhnazarov, T. Kh. and Orochko, D. I., Investigationof the structure of a non-uniform fluidised bed, *International Chemical Eng*ineering, **9**,263 (1969).

[2] Wu, C. S. and Whiting, W. B., Interacting jets in a fluidised bed, *Chemical Engineering and Communications*, **73**, 1 (1988).

[3] Blake, T.B., Webb, H., Sunderland, P.B., The non-dimensionalisation of equations describing fluidisation with application to the correlation of jet penetration height,*Chemical Engineering Science*, **45**, 365 (1990).

[4] Mathur, K. B. and Gishler, D. E., A technique for contacting gases with coarse solid particles, *Journal of American Institute of Chemical Engineers*, **1**, 157 (1955).

[5] Merry, J. M. D., Penetration of vertical jets into fluidized beds, *Journal of American Institute of Chemical Engineers,* **21**, 507 (1975).

[6] Yang, W. C. and Keairns, D., Estimating the jet penetration depth of multiple vertical grid jets, *Industrial Engineering Chemistry and Fundamentals*, **18**, 317 (1980).

[7] Richner, D.W, Minoura, T., Princhet, J.W. and Blae, T.R., Computer simulation of isothermal fluidization in large scale laboratory rigs, *Journal of American Institute of Chemical Engineers*, **36**, 361 (1990).

[8] Hong, R.H., Li, H.Z., Li, H. B. and Wang, Y., Studies on the inclined jet penetration length in a gas-solid fluidized bed, *Powder Technology*, **92**, 205 (1997).

[9] Hong, R.Y., Guo, Q.J., Luo, G.H., Zhang, J.Y. and Ding, J., On the jet penetration height in fluidized beds with two vertical jets, *Powder Technology*, **133**, 216 (2003).

[10] Massimilla, L. “Gas jets in fluidised beds”, in: Davidson, J.F., Clift, R., and Harrison, D., (Eds.), Fluidisation II, Academic Press, London, p.133 (1985).

[11] Lefroy, G.A. and Davidson, J.F., The mechanics of spouted beds, *Transactions of Institution of Chemical Engineers*, **47**, T120 (1969).

[12] Massimilla, L. and Westwater, *Journal of Institute of Chemical Engineers*, **9**,132 (1959).

[13] Suciu, G.C. and Patrascu, M., Particle circulating in a spouted bed, *Powder Technology*, **19**, 109 (1978).

[14] Chiba, T., Terashima, K. and Kobayashi, K., Lateral distribution of bubble sizes in two dimensional gas-fluidised beds, *Journal of Chemical Engineering of Japan*, **6**, 167 (1975).

[15] Saxena, S.C., Marthur, A. and Sharma, G.K., Bubble dynamic and elutriation studies in gas fluidized beds, *Chemical Engineering and Communications*, **20**, 35 (1984).

[16] Van Velzen, D. V., Flamm, H.J., Langenkamp, H., Casile, A., Motion of solids in spouted bed, *Can. J. Chemical Eng.,* **52** 156 (1974).

[17] Roy, D., Larachi, F., Legros, R. and Chauoki, J., A study of solids behaviour in a spouted bed using 3-D tracking, *Canadian Journal of Chemical Engineering*, **52**, 561 (1994).

[18] Stein, M., Ding, Y. L. and Seville, J. P. K., Experimental verification of the scaling relationships for bubbling gas fluidised beds using the PEPT technique, *Chemical Engineering Science*, **57**, 3649 (2002).

[19] Bolous, M. I. and Waldie, B., High Resolution Measurement of Particle Velocities in a Spouted Bed Using Laser-Doppler Anemometry, *Canadian Journal of Chemical Engineering*, **64**, 939 (1986).

[20] He, Y.L., Lim, C.J., Grace, J.R., Zhu, J.X. and Qin, S.Z., Particle velocity profile and solid flow pattern in spouted beds, *Canadian Journal of Chemical Engineering,* **72**, 229 (1994).

[21] Makkawi, Y. T. and Wright, P. C., The voidage function and effective drag force for fluidized beds, *Chemical Engineering Science,* **58,** 2035 (2003).

[22] Lim, K. S., Agarwal, P. K. and O’Neill, B. K., Measurement and modelling of bubble parameters in

a two-dimensional gas fluidized bed using image analysis, *PowderTechnology*, **60**, 159 (1990).

[23] Lim, K. S., Agarwal, P. K., Bubble velocity in fluidized beds: the effect of non vertical bubble rise on its measurement using submersible probes and it's relationship with bubble size, *Powder technol.*, **69**, p. 239(1992).

[24] Agarwal, P. K., Hull, A. S. and Kim, K. S., Digital image analysis techniques for the study of bubbling fluidized beds, in Chapter 12 of "Non-invasive monitoring of multiphase flows", Chaouki, J., Larachi, F. and Dudukovic, M.P., (Eds), p. 407 (1996).

[25] Saadevandi, A. and Turton, R., The application of computer-based imaging to the measurements of particle velocity and voidage profiles in a fluidized bed, *Powder Technology*, **98**, 183 (1998).

[26] Goldschmidt, M.J.V., Link J. M., van Swaaij, W. P. M., "Fluidization X" Hydrodynamic modeling of dense gas-fluidized beds: validation of a multi-fluid continuum model with non-intrusive digital image analysis measurements, Kwauk, M., Li, J. and Yang W.C., (Eds.), p.405 (2000).

[27] Goldschmidt, M.J.V., Hydrodynamic modelling of fluidized bed spray granulation, PhD thesis, (2001). Hong, R.H., Li, H.Z., Cheng, M.Y., and Zhang, J.Y., Numerical simulation and verification of a gas-solid jet fluidised bed, *Powder Technology*, **87**, 73 (1996).

[28] Stein, M., Ding, Y.L., Seville, J.P.K. and Parker, D.J., Solids motion in gas bubbling fluidised beds, *Chemical Engineering Science,* **55**, 5291 (2000).

[29] Abramovich, G. N., The theory of turbulent jets, M.I.T. Press,Cambridge, Massachusetts (1963).

[30] Michele, G. De., Elia, A. and Massimilla, L., The intraction between jets and fluidized beds,*Ing. Chim. Ital.,* **12** (11-12) (155-162) (1976).

[31] Schlichting, H., *Grrenzschicht-theorie*, Vol. 5, Verlag G.Braun, Karlsruhe, Auflage (1965).

[32] Donsi, G., Massimilla, L. and Colantuoni, L., The dispersion of axi-symetric gas jets in fluidized beds, in grace and matsen(eds), "fluidization", Plenum, New York, 1(980).

[33] Aisa, L., Garcia, J. A., Cerecedo, L. M., Garcia Palacin, I., Calvo, E., Particle concentration and local mass flux measurements in two-phase flows with PDA. Application to a study on the dispersion of spherical particles in a turbulent air jet, *International Journal of Multiphase flow*, **28** p. 301 (2002).