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# Effect of air flowrate on particle velocity profile in a circulating fluidized bed

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**Abstract**−The research was conducted in a cold flow circulating fluidized bed (CFB). The diameter and height of riser are 5 and 200 cm, respectively. The objective is to study effect of gas velocity on hydrodynamic of glass beads having mean diameter of 547 micron and density of 2,400 kg/m$^3$. The measurement of particle velocity profile was achieved by using a high-speed camera and an image processing software. A probe of 0.5 cm in diameter was inserted into the riser at the height of 110 cm from gas distributor and was set at 3 positions along the radius of the riser; 0, 0.6, and 1.8 cm from center. Transport velocity ($U_{tr}$), core-annulus velocity ($V_{CA}$) and minimum pneumatic velocity ($V_{mp}$) were employed in determining solid flow pattern in the riser. It was observed that the flow regimes changed from fast fluidization to core-annulus and to homogeneous dilute bed when the gas velocities increased from 7, 8 and 9 m/s, respectively. The results from high-speed camera showed that glass beads velocity existed a maximum value at the center of the riser and gradually decreased toward the wall for all three gas velocities. It was also found that most of solid traveled upward in the core of the riser, however, solid traveled downward was identified at the wall layer.

Key words: CFB, Glass Beads, Particle Velocity Profile, High-speed Camera

## INTRODUCTION

Circulating fluidized beds (CFB) have been widely used in the many industrial processes due to many advantages such as uniform temperature distribution, high gas-to-particle mass and heat transfer rates and flexible operation. The common industrial applications include fluid catalytic cracking (FCC) and coal combustion. The CFB system consists of a riser that expands vertically, a cyclone and a downcomer. The two-phase mixture exits at the top of the riser and is subsequently separated using cyclone with the gas removed off the top, while the solid particles are returned to the base of the riser via a downcomer. In a core-annular flow, the particles are more at the walls of the bed moving down forming an annulus, and the gas with less particles are more at the center moving upward to form the core. The hydrodynamics of CFB is influenced by gas velocity, solid circulation rate, physical properties of particles such as size, sphericity and density. Choi et al. [1] examined the effect of gas velocity and initial solid loading on the solid circulation rate, and the solid holdups in the riser and standpipe. They reported that the solid circulation rate increases with increases in the gas velocity in the riser and in the initial solid loading. And they also found that the average voidage in the riser slightly increases with increases in the gas velocity. The objective of this research was to study the influence of gas velocity on the flow pattern and direction of glass beads in the cold flow CFB.

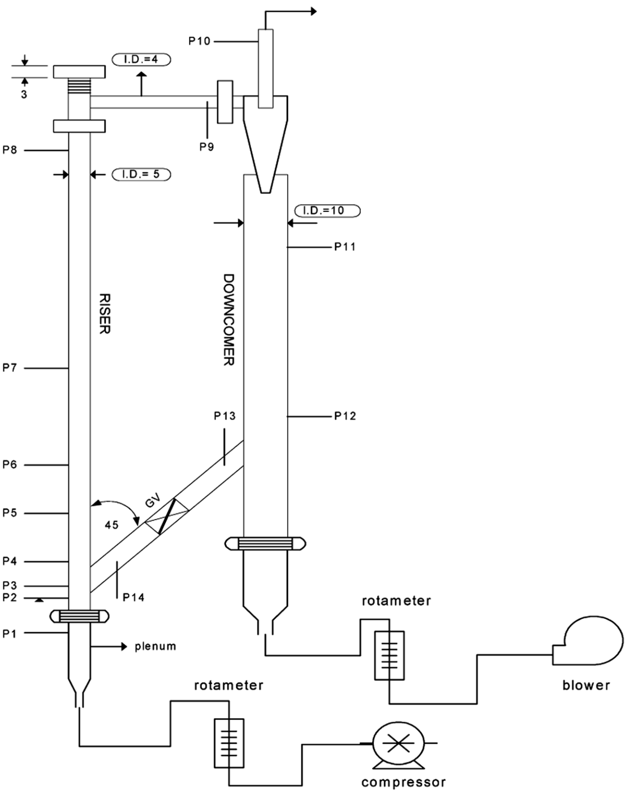


**Fig. 1. Circulating fluidized bed.**

## EXPERIMENTAL SETUP

A schematic of the cold flow CFB in which experiments were carried out is shown in Fig. 1. The riser is 200 cm high with 5 cm ID and the downcomer is 150 cm high with 10 cm ID. Fourteen pressure taps are mounted around solids circulating loop to determine the pressure drop of the system. The air flow rates were regulated by control valves and measured with rotameters. Compressed air entered riser through a porous plate gas distributor at the bottom and carried solid particles upward. At the top of riser, particles carried over were fed to cyclone in which most of them were removed from the air stream and returned to the downcomer. The exhausted air exited the apparatus through a bag filter. Particles in the down-

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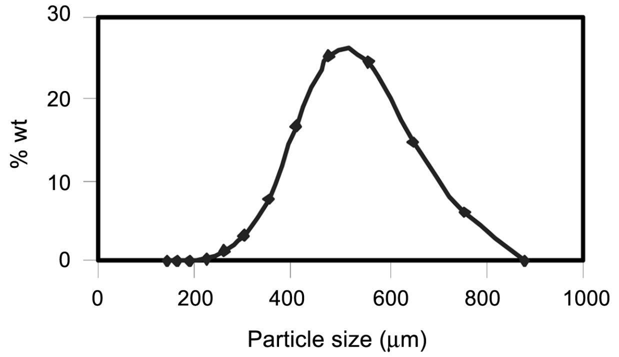


**Fig. 2. Glass beads size distribution.**

comer were in bubbling fluidized state by air from blower and transported back to riser via the 45 degree inclined standpipes. The solid particles used in this experiment were glass beads with wide size distribution from 140-847 micron. The mean diameter and density are 547 micron and 2,400 kg/m$^3$, respectively. The size distribution of glass beads, shown in Fig. 2, measured by particle size laser analyzer (Malvern Instruments Ltd.) The solid circulation rate was computed based on measuring the time required to remove all solids from the riser of CFB after cutting solids flow under different gas velocities and was in the range of 23-31 kg/m$^2$-s.

Radial particle velocity in the riser was measured using PIV technique [2]. The system consists of a high-speed camera, a fiber optic light source, a probe, and a personal computer with image processing software. The camera has 10 electronic shutter settings from 1/50 to 1/10,000 sec. A probe of 0.5 cm in diameter was inserted to get a view in the riser at the height of 110 cm from gas distributor and was set at 3 positions along the radius of the riser; 0, 0.6, and 1.8 cm from center. At the tip of the probe there was a thin glass piece cover to prevent solid from escaping the system. The camera was focused through the probe into the riser and was connected to a personal computer, which has a micro-imaging board and image processing software for data measurement and analysis.

The PIV setup and the probe locations are shown in Fig. 3. A rotating colored transparent disk was placed in front of the light source to determine the direction of the particles by observing order of the colors in the streak image. The zoom and focus settings were set to maximum to get minimum depth of the control volume. Fig. 4. shows typical streak lines generated on the computer screen. These streak

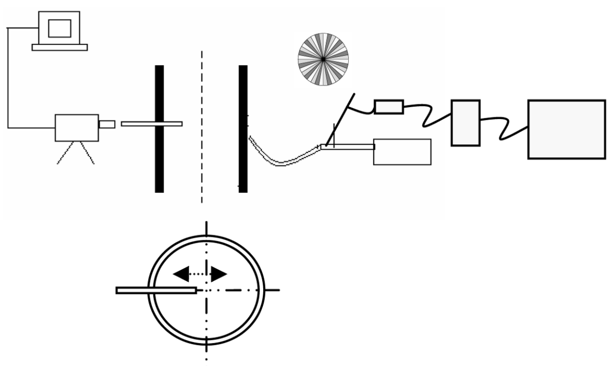

**Fig. 3. Particle image velocity measurement system.**

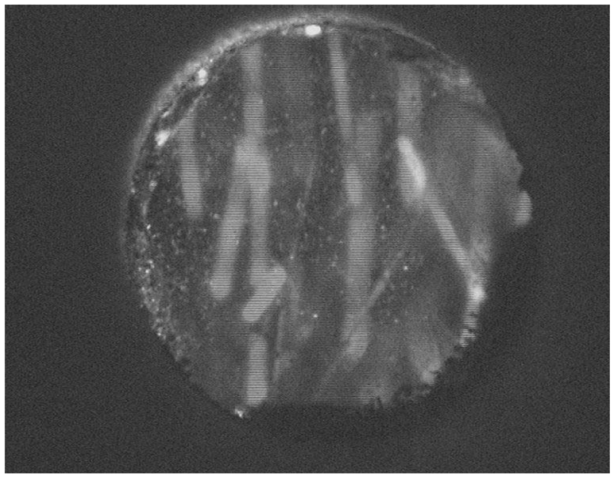

**Fig. 4. Typical streak lines captured by PIV technique.**

lines represented the space traveled by the glass beads in a given time interval specified on the camera. The long thin lines corresponded to small particles while the short thick lines denoted large particles. The particle velocity in radial and axial directions were estimated by dividing the respective distance by time, as shown in Eq. (1).

$$C_r=(L/t)\cos\alpha$$
$$C_z=(L/t)\sin\alpha \qquad (1)$$

Where L is the distance traveled or streak length, t is the time elapsed by glass beads, which is the inverse of the shutter speed of the camera, and $\alpha$ is the angle from horizontal.

## EXPERIMENTAL RESULTS

### 1. Flow Pattern in Riser

Various solid flow patterns such as turbulent, fast fluidization, core-annulus and homogenous dilute bed could be found in the riser depending on gas velocity, solid circulation rate, and physical properties of solids. Gas velocity is an important parameter for the design and operation of a circulating fluidized bed riser. In this research, transport velocity, core-annulus velocity and minimum pneumatic velocity were used to determine the flow regimes.

The transport velocity determines the minimum gas velocity required to bring the riser from the turbulent flow regime to a stable fast fluidization flow regime [3]. In the literature, there are several techniques available to determine this transport velocity [4]. In this study, transport velocity was estimated by observe the pressure drop across the riser bottom at different gas velocities and solid circulation rates. From Fig. 5, the transport velocity was the lowest gas velocity with a pressure drop dependent on the solid circulation rate and was found to be 4.8 m/s. The transport velocity obtained was compared with the predicted values based on the available correlation given in Table 1.

The core-annulus velocity ($V_{CA}$) and minimum pneumatic velocity ($V_{mp}$) were the gas velocity required to bring the riser from the fast fluidization regime to a core-annulus and from core-annulus to homogeneous dilute bed, respectively [5]. Based on the following expressions (Eq. (2) and (3)), the core-annulus velocity ($V_{CA}$) and

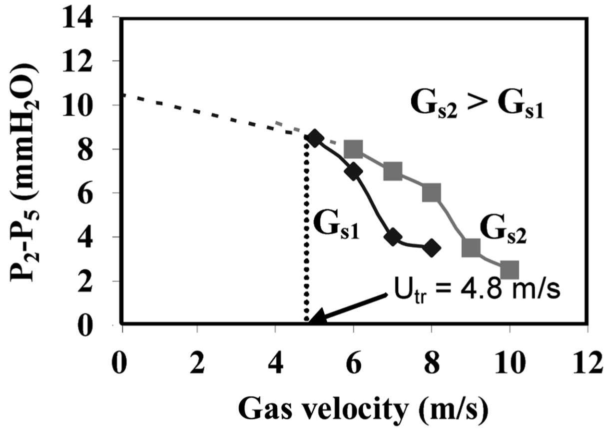


**Fig. 5. Transport Velocity ($U_{tr}$) of glass beads 547 micron.**

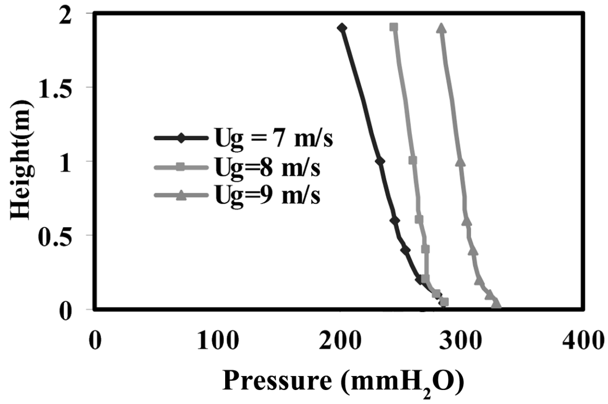


**Fig. 6. Pressure profiles along the height of the riser at different gas velocities.**

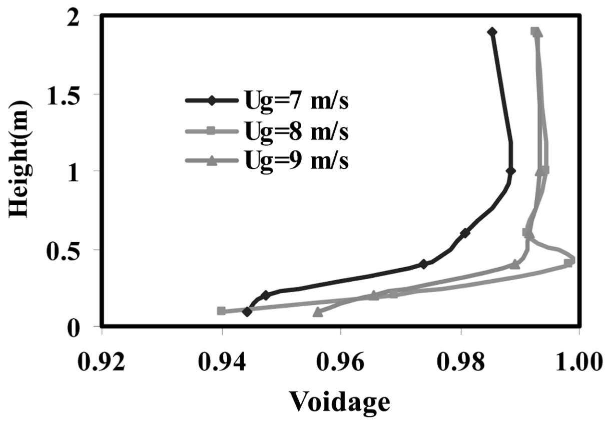


**Fig. 7. Voidage profiles along the height of the riser at different gas velocities.**

**Table 1. Comparison of transport velocity from correlation and this work**

| References | Correlation | $U_{tr}$ (m/s) |
|---|---|---|
| Bi [5] | $Re_t$=1.53 $Ar^{0.5}$ | 5.09 |
| Smolders [3] | $Re_t$=1.75 $Ar^{0.468}$ | 4.30 |
| Perales [11] | $Re_t$=1.41 $Ar^{0.483}$ | 4.00 |
| Adanez [12] | $Re_t$=2.078 $Ar^{0.463}$ | 4.87 |
| This work | | 4.80 |

**Table 2. Possible glass beads flow pattern in this research**

| Range of $U_g$ (m/s) | Flow pattern |
|---|---|
| 4.8-7.8 | Fast fluidization |
| 7.8-8.3 | Core-annulus |
| >8.3 | Homogeneous dilute bed |

minimum pneumatic velocity ($V_{mp}$) were 7.8 and 8.3 m/s, respectively.

$$\frac{V_{CA}}{\sqrt{gd_p}} = 21.6Ar^{0.105}\left(\frac{G_s}{\rho_g V_{CA}}\right)^{0.542} \tag{2}$$

$$V_{mp} = 10.1(gd_p)^{0.347}\left(\frac{G_s}{\rho_g}\right)^{0.310}\left(\frac{d_p}{D}\right)^{-0.139}Ar^{-0.021} \tag{3}$$

Table 2 shows possible glass beads flow pattern in this research.

**2. Pressure Profile in the Riser**

For each set of operating conditions, axial profiles of pressure were measured along the riser by means of electronic pressure transducers. Voidage, $\varepsilon$, were calculated by processing the pressure, $\Delta P$, measured at successive pressure taps. When acceleration contribution and friction effects at the riser walls were discarded. The relationship $\Delta P=\rho_s(1-\varepsilon)gL$ was used; $\rho_s$ and g being the particle density and the acceleration due to gravity, respectively [6]. The pressure and axial voidage profiles in the riser are shown in Fig. 6 and 7. The results findings were similar to previous researchers [1,7] in such a way that pressure in riser increased with increasing superficial gas velocity but decreased along the height (Fig. 6), and the axial voidage profile showed a dense section at the very bottom part of the riser, then increased as solid traveling upward (Fig. 7). It clearly showed that at gas velocity of 7 m/s solid hold-up was high along the height and it was confirmed by eye observation during experiment. As can be seen from the CFB setup in Fig. 1, the riser exit is at a sharp right angle to the vertical flowing. The glass beads cannot tolerate the sharp turn and recirculate internally down along the walls of the riser [8]. As a result, an area of densification is created along the riser height.

**3. Time Average Hydrodynamic Particle Velocities**

As gas velocity increased from 7 to 9 m/s, the solid circulation rate increased from 23 to 31 kg/m$^2$-s. For each measuring point, 0, 0.6, 1.8 cm along the radial position, the high-speed camera captured a total of 1,200 frames of particle streak images. Only the frames with clear streak images were collected. The particle velocity was calculated by Eq. (1). The solid velocity profiles as a function of radial position is shown in Fig. 8 with a solids circulation rate in the range of 23-31 kg/m$^2$s. As can be seen in Fig. 8a, the time average axial solid velocity increased with increasing gas velocity. At gas velocities of 7 and 8 m/s, the solid velocities near the wall were 46% less than those of in the center, therefore, the glass beads should be in fast fluidization and core-annulus flow pattern, respectively, consistent with that finding in Part I. Mathiesen [9] stated that the core-annulus flow was characterized by a nearly constant particle upflow called the core-region while the annulus region showed a downflow of solid. However at gas velocity of 9 m/s the solid velocities

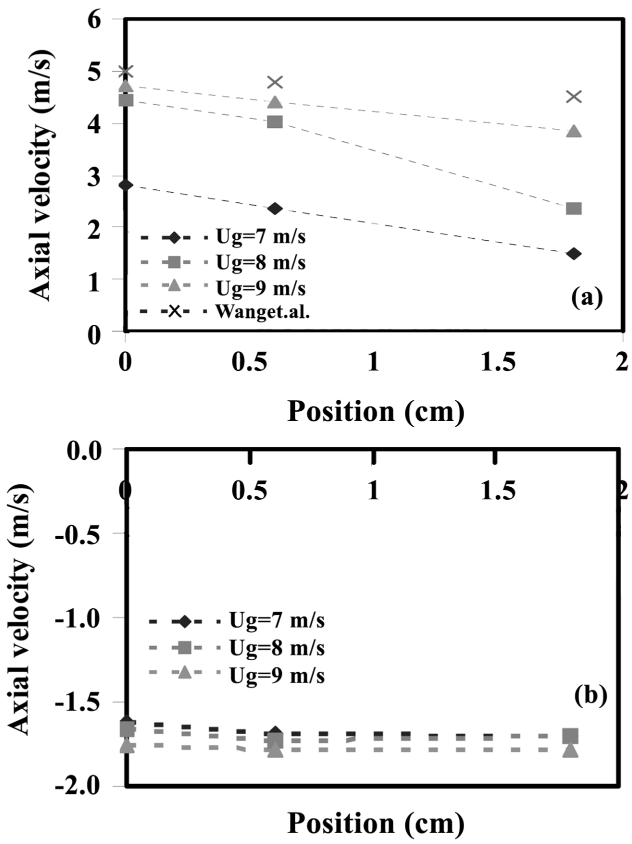


**Fig. 8. Solid axial velocity profiles along radial position a) moving upward (b) moving downward.**

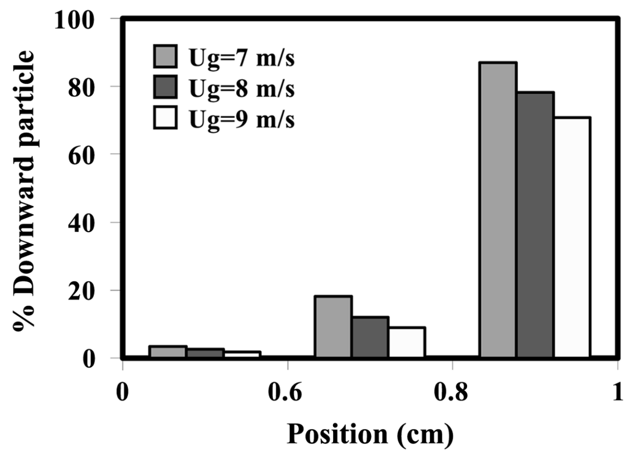


**Fig. 9. Particle holdup moving downward as a function of radial position at different $U_g$ and 110 cm high from distributor.**

along the radius were slightly difference within 20%, the glass beads flow regime should be in homogeneous dilute bed. This trend is consistent with the results reported previous by Wang [10] who used FCC particle in 10.2 tall riser at gas velocity of 10 m/s. Fig. 8b shows the average glass beads downward velocity which appeared to be insensitive to operating conditions.

Particle holdup moving downward as a function of radial position are shown in Fig. 9. The number of particle moving downward was found to decrease with increasing gas velocity and increase with radial position.

## CONCLUSIONS

The effect of gas velocity on hydrodynamic of glass beads in the cold flow CFB riser was studied. The transport velocity obtained from experiment was closed to those predicted by correlations. As gas velocities increased from 7-9 m/s, the flow pattern of glass beads was found to change from fast fluidization, core annulus, and homogeneous dilute bed regimes, respectively. By using a high-speed camera and an image processing software, the time average hydrodynamic solid velocities were found to decrease toward the wall probably due to a core-annulus flow pattern at gas velocities of 7 and 8 m/s. Because of the flat profiles of downward velocities, it could be concluded that the downward velocities were independent on both gas velocity and radial position.

## ACKNOWLEDGEMENT

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## NOMENCLATURE

Ar : Archimedes number $(=\rho_g(\rho_s-\rho_g)gd_{sv}^3/m^2)$ [-]
$C_r$ : particle velocity in radial [m/s]
$C_z$ : particle velocity in axial [m/s]
D : riser or bed diameter [m]
$d_p$ : particle size [m]
$d_{sv}$ : particle surface-to-volume diameter [m]
$G_s$ : solid circulating [kg/m$^2$ s]
g : gravitational constant [m/s$^2$]
L : distance traveled or steak length [m]
$Re_{TR}$ : Reynolds number for the transport velocity $(=\rho_g U_{TR} d_{sv}/m)$ [-]
t : time elapsed by glass beds [s]
$U_g$ : superficial gas velocity [m/s]
$U_{tr}$ : transport velocity [m/s]
$V_{CA}$ : core-annulus velocity [m/s]
$V_{mp}$ : minimum pneumatic [m/s]
L : height of the riser [m]
$\Delta P$ : pressure drop across the riser [mm$H_2O$]
$\Delta P/\Delta L$ : pressure gradient [mm$H_2O$/m]
$\varepsilon$ : voidage [-]
$\alpha$ : angle from horizontal
$\rho_g$ : gas density [kg/m$^3$]
$\rho_s$ : particle density [ kg/m$^3$]

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