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Measurements of solid concentration and particle velocity distributions near the wall of a cyclone

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ABSTRACT

The particle velocity and concentration distribution in the near-wall region of the cyclone were experimentally studied. A series of measurements were conducted with fiber optical probes (FOPs). It was found the radial solid concentration distribution is severe non-uniform and particles agglomerate as dense spiral bands near the wall, moving downwards with a certain interval. On the cross-section plane, from the center to the wall, solid concentration increases. The average solid concentration near the wall increases with the gas velocity or solid concentration at the cyclone inlet. Along the moving particle bands, solid concentration increases and particle average velocity decreases. Under present experimental conditions, the thickness of the particle bands in the cylindrical section is about 4–12 mm. Particle velocity in the near-wall region is in the range of 0.5–2.5 m/s and its average value is insensitive to the operational parameters. The number of spiral bands increases with the cyclone's inlet gas velocity, and might be greatly influenced by the cyclone structure.

1. Introduction

Cyclones are commonly used as the gas–solid separators in many industrial applications due to their high separation efficiency, simple structure, excellent adaptability and cost-effectiveness. Understanding the gas–solid flow dynamics inside the cyclone is important to predict the cyclone's separation efficiency and pressure drop [1–4]. Besides, it is also important to describe inside chemical reaction for some applications such as coal-fired circulating fluidized bed (CFB) boilers [5] or biomass gasifiers [6].

The gas–solid flow in the cyclone is very non-uniform. When the flow stream of solid–gas mixture is tangentially injected into the cyclone, solid particles, subjected to the centrifugal force, are concentrated in the wall region, spirally rotating downwards to a particle collector. At the same time, gas flow with a small amount of particles escapes from the vortex finder. Previous studies found that when particle loading at the inlet exceeds a certain critical value, most particles aggregate into regular bands near the wall [7]. CFB boilers are usually operated at rather high particle loading, e g., 5 kg particles/kg gas [7], and the particle loading greatly exceeds the critical loading [7,8]. Thus, studies on the particle motion and concentration distribution in the near-wall region are of significant, particularly for cyclones with inside gas–solid reactions.

A few studies have been conducted but not adequate on the gas–solid flow near the wall especially when particle loading is large. Zhou and Soo [9] measured tangential velocity distribution of the particles in the center of a cyclone at low solid concentration using a Laser Doppler Velocimeter (LDV). Mothes and Löffler [10] measured the particle concentration distribution by probe sampling method but at the locations relatively far away from the wall ($r/R < 0.8$), where r is the radial distance from the center and R is the cylindrical diameter of the cyclone. Boysan et al. [11] numerically simulated the particle trajectory in the cyclone vortex. Muschelknautz and Röper [12] assumed that the solids velocity near the wall is about several meters per second and the layer thickness is of several millimeters in the cyclone used in a CFB boiler. However, no experimental data were reported. More recently, Chan et al. [13] experimentally studied the particle motion in the cyclone with the technique of positron emission particle tracking (PEPT). They found that the average tangential and axial velocity over the length of the cylindrical body for the near-wall particles was between 1.5–2 m/s and 0.9–1.3 m/s, respectively. However, no volumetric solid concentration of near-wall particles was measured. The authors of this paper conducted some preliminary measurements on the volumetric solid concentration and velocity of near-wall particles with a fiber optical probe (FOP) [14].

The turns of spirally moving particle band on the cyclone wall, N_s, can be used to estimate the particle holdup [15] and separation efficiency [16,17] in the cyclone, and post-combustion of a CFB boiler [15]. However, the findings on N_s are debating. Some researchers proposed N_s is a constant [16,17], while some others

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Nomenclature

a	coefficient in the calibration function (Eq. (1))
$C_{s,in}$	solids concentration at cyclone inlet (kg/m^3)
C_v	volumetric solid concentration
$C_{v,0}$	volumetric solid concentration in a fixed bed
d_p	mean diameter of particles (μm)
D	thickness of the continuous particle layer at the wall (mm)
G_s	circulating rate (kg/s)
l	length that particles traveled in the cyclone (m)
L	distance from the wall on a cross-section plane (mm)
N_s	the absolute total number of turns observed on the cyclone wall
r	radial distance of the particle to the center (m)
R	cylindrical diameter of cyclone (m)
$\bar{t}_r$	particle's average residence time (s)
u_s	local particle velocity (m/s)
$\bar{u}_s$	mass-based average velocity of near-wall particles (m/s)
U	measured signal intensity (V)
U_0	measured signal intensity at $C_v = 0$ (V)
V_{in}	gas velocity at cyclone inlet (m/s)
W	width of the particle layer (m)

Greek letters

ρ_b	bulk density of particles (kg/m^3)
ρ_r	real density of particles (kg/m^3)
ω	rotational angular velocity (1/s)

proposed that N_s is a function of gas velocity at cyclone inlet, V_{in} (m/s) [18].

In this research, based on our previous study [14,15], experiments were further conducted to investigate the volumetric solid concentration and velocity distribution of near-wall particles and the geometrical characteristics of the spiral band.

2. Experimental

2.1. Experimental system

The experimental system is shown in Fig. 1, in which the riser, cyclone, standpipe and loopseal form a circulating loop of the circulating fluidized bed. Most of the apparatus was made of plexiglass for observation. The riser has a height of 5 m and an inner diameter of 0.2 m. Several measuring holes were opened at different locations on the cyclone surface, and 3 of them (Points 1, 2 and 3) were located along the moving particle spiral bands in the cylindrical section of the cyclone. The geometry of the cyclone is illustrated in Fig. 2.

During the experiments, the gas flow rate was measured by a vortex flowmeter and controlled by adjusting the damper openness of the valves connected to the forced draft fan and the induced fan. The circulating rate, G_s (kg/s) was measured by weighting the particles collected on an electric stop valve installed at the middle of the downcomer in a given time. The aeration flow at the loopseal was provided separately from an air compressor. The pressure drop at different locations of the riser and the cyclone were measured by the pressure sensors. Some more description of the experimental system was given in previous studies [15,19].

After the system was in steady for a certain period at a given fluidizing gas velocity and static height of bed material in the downcomer, G_s was measured. Then measurements of the volumetric

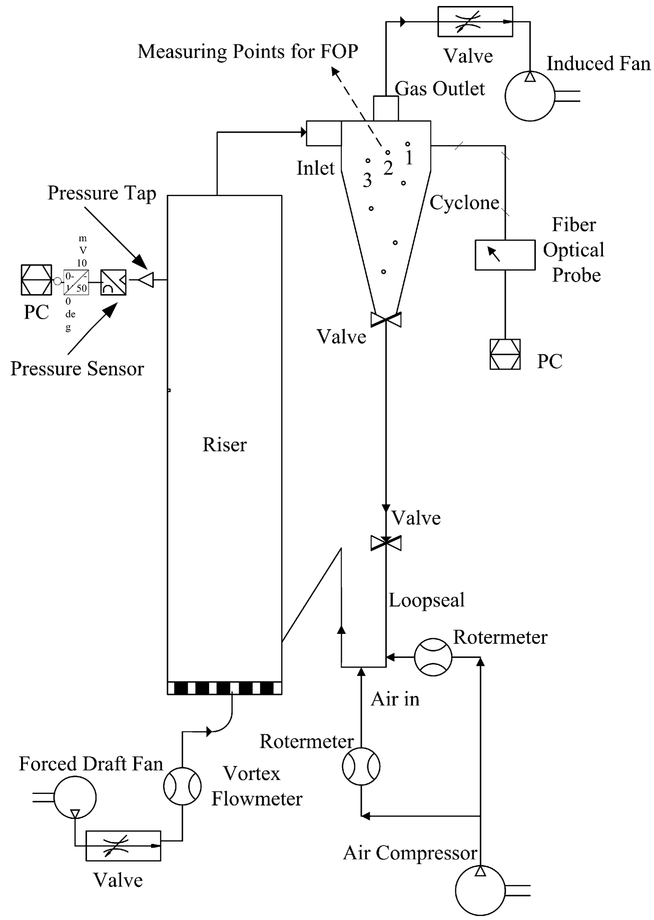

Fig. 1. Schematic of the experimental system.

solid concentrations and particles velocities at different radial positions of the measuring points were taken by using a fiber optical probe (FOP).

The particle motion on the outer surface of the cyclone was recorded by a camera under different operation conditions. A reference ruler was hanged on the outer wall of the cyclone for measuring the width of the particle layer, W.

The experimental variables included gas velocity at the cyclone inlet V_{in} (m/s), circulating rate G_s and solid concentration at cyclone inlet $C_{s,in}$ (kg/m^3). Quartz sand was used as bed material. The properties of the bed material and the operational parameters used in the experiments can be found in Table 1.

2.2. Calibration of the fiber optical probe

Fiber optical probe (FOP) method was used to measure the particle velocity and volumetric solid concentration near the wall in the cyclone. With proper design and application setup, this simple and relatively inexpensive method can have high signal-to-noise ratios while with minor disturbance to the flow [14,20,21]. Moreover, it is more available than other method for the measurements of a dense

Table 1
Bed material properties and operational parameters.

d_p (μm)	260
ρ_b (kg/m^3)	1550
ρ_r (kg/m^3)	2650
$C_{v,0}$	0.585
V_{in} (m/s)	8.9, 13.3, 17.4, 19.7, 22.2 and 25.3
$C_{s,in}$ (kg/m^3)	2.5–5.7

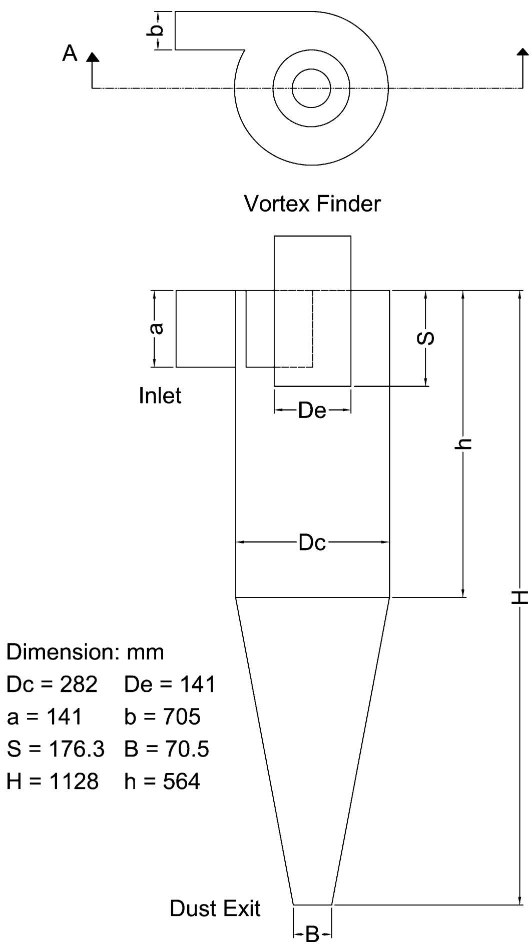

Fig. 2. Cyclone geometry.

gas solid flow [21–23]. The principle of the FOP can be found in the literatures [24,25].

The both probes used for velocity and volume-fraction measurements had an outer diameter of 3.8 mm. Inside the probes, there were many emitting and receiving quartz fibers. The velocity probe had two bundles of fibers with an average separation distance of 1.93 mm. The size of fiber bundles was slightly less than that measured particles, and thus the emitting light could be reflected by the particle.

The calibration procedure of the velocity probe was similar to that conducted by Tayebi et al. [21] and Zhu et al. [23]. An average-size particle was glued at a radius of r (m) on a thin, black rotating disk, which was driven by a variable speed motor. The linear velocity of the particle u_s (m/s) was the product of r and the angular velocity ω (1/s) measured by a tachometer. By changing the rotating speed of the disk, different particle linear velocities were obtained. The values of u_s measured by velocity probe were in very good agreement with the preset ones, as shown in Fig. 3.

With a prior accurate calibration, the reflected light intensity received by the volume-fraction probe, i.e., the output voltage was correlated with the volumetric solid concentration in the form of power function as given in Eq. (1) [20,21]:

$$U - U_0 = aC_v^k \quad (1)$$

where U was measured signal intensity (V); C_v was volumetric solid concentration; and U_0 was signal intensity at $C_v = 0$; and a and k were constants. The calibration was done in a fixed bed and in a dilute region of a well-fluidized bed as introduced in the previous works [24,26]. For our study, $k = 0.588$ and $a = 6.55$.

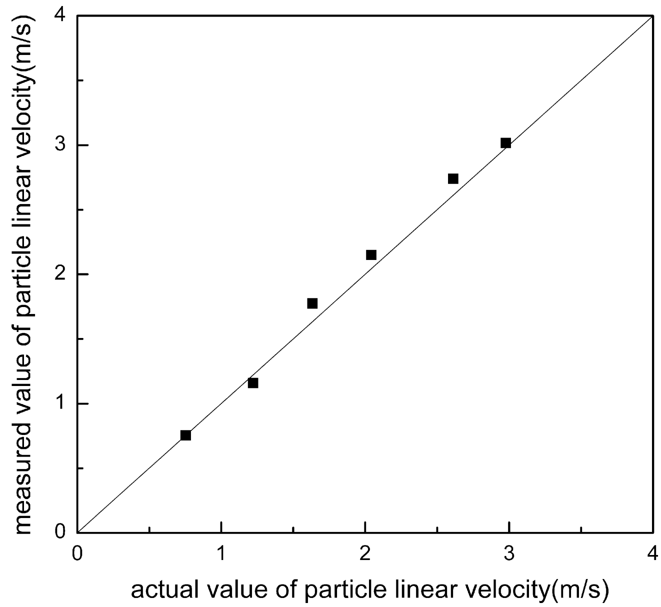

Fig. 3. Comparison between measured value and actual value of local particle velocity.

3. Results and discussion

3.1. Volumetric solid concentration near the wall

In the experiments, it was found that solid particles were mostly concentrated in the near-wall particle layer, and their concentration C_v changed with V_{in} and $C_{s,in}$. Shown in Figs. 4 and 5, at the same location Point 2, C_v increases with the increase of V_{in} at a constant $C_{s,in}$, and it increases with $C_{s,in}$ at a constant V_{in}.

The influence of V_{in} and $C_{s,in}$ on C_v is straightforward. Centrifugal force is the driving force for the particle separation in the cyclone. At a constant $C_{s,in}$, the particle velocity u_s and the centrifugal force on particles increase with the increasing of V_{in}. The greater is the centrifugal force, the higher tendency for the particles to move toward the wall, and thereby the larger C_v at the wall is.

Fig. 6 shows the distributions of C_v at three measuring points, Points 1, 2 and 3 along the particle band, when V_{in} = 17.4 m/s and

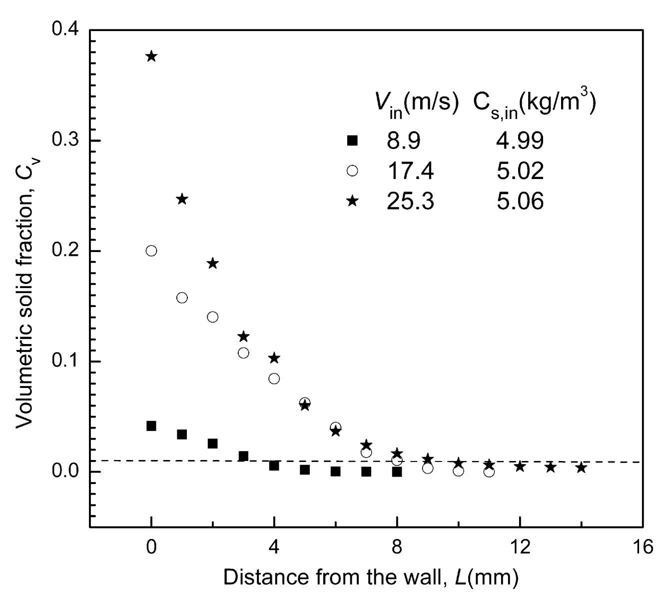

Fig. 4. The influence of inlet gas velocity on volumetric solid concentration.

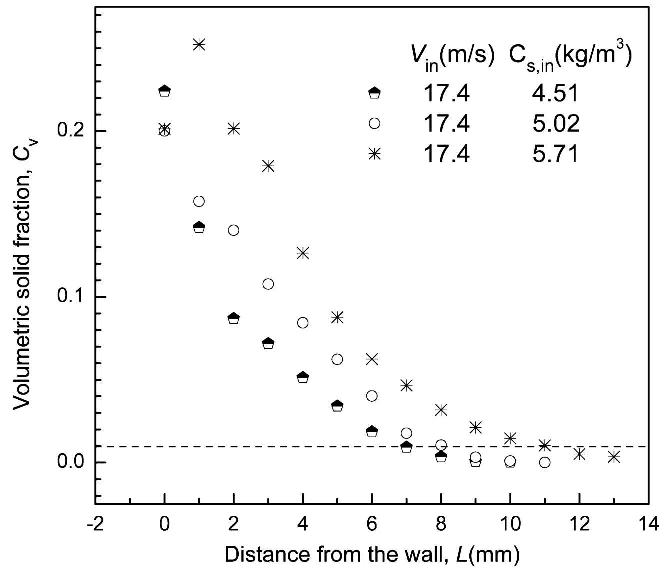

Fig. 5. The influence of inlet solid concentration on volumetric solid concentration.

$C_{s,in}$ = 5.71 kg/m^3. It is obvious that C_v increases along the moving direction of the near-wall particles, indicating that more particles aggregate or the particle velocity decreases in the near-wall layer.

The thickness of the continuous particle layer near the wall, D (mm), is defined as the distance from the wall to the location where C_v = 0.01. Shown in Figs. 4–6, D is in the range of 4–12 mm, validating the assumption of Muschelknautz and Röper [12].

It is worth to point out that for cyclones used in the CFB boiler, the thickness of the particle layer near the wall may be much larger than the experimental one. The cylindrical section of those cyclones is usually several meters in diameter and the inlet is much wider than that used in current experiments. At the same inlet solid concentration, more particles move to the wall under centrifugal force.

3.2. Velocity distribution of near-wall particles

The radial distributions of near-wall particle velocity u_s were measured under different V_{in} and $C_{s,in}$. Since the radial velocity of near-wall particles was very small, u_s was basically the resultant velocity of tangential velocity and axial velocity. Fig. 7 shows that radial distributions of u_s under different V_{in} and $C_{s,in}$ are similar: u_s first decreases then increases with the increase of L. In addition, u_s is in the range of 0.5–2.5 m/s, close to that reported by Chan et al. [13].

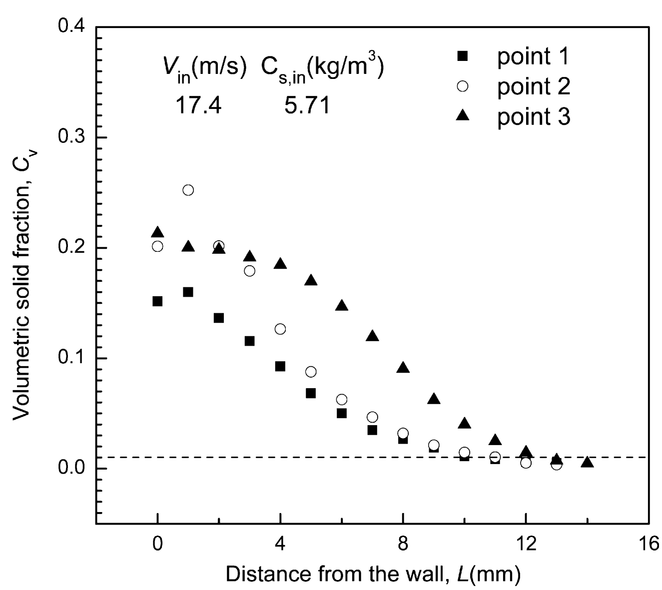

Fig. 6. Volumetric solid concentration distribution at different measuring locations.

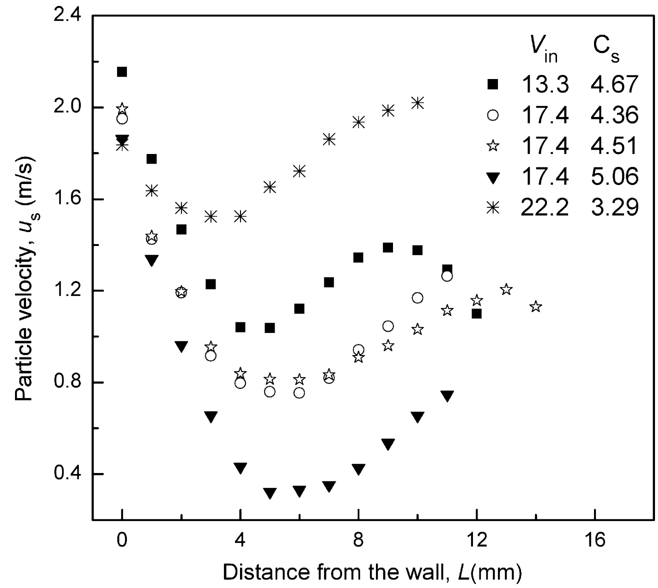

Fig. 7. Radial distributions of the particle velocity under different inlet gas velocity and inlet solid concentration.

The mass-based average velocity $\bar{u}_s$ (m/s) is often used to describe the overall particle motion, and it can be calculated by

$$\bar{u}_s=\sum_{i=1}^{k}u_{s,i}\left(\frac{l_t W\rho_r u_{s,i}C_{v,i}}{l_t W\rho_r\sum_{i=1}^{k}u_{s,i}C_{v,i}}\right)=\sum_{i=1}^{k}u_{s,i}\left(\frac{u_{s,i}C_{v,i}}{\sum_{i=1}^{k}u_{s,i}C_{v,i}}\right) \quad (2)$$

In Eq. (2), k is the number of measuring step the probe moves along the radial direction; l_t is the interval the probe moved in each step, in our study l_t = 1 mm; W (m) is the width of the spiral particle band. $u_{s,i}$ (m/s) and $C_{v,i}$ is the particle velocity and volumetric solid concentration measured in the ith step respectively. Based on Eq. (2), at Point 2, $\bar{u}_s$ was in the range of 1.5–2.5 m/s. The results confirmed the assumption of Muschelknautz and Röper [12].

In the cyclone, particle's radial velocity is proportional to the square of the tangential velocity and the particle diameter [4]. Thus, particles with larger velocity or of larger size move more quickly towards the wall from the same radial positions. Given that the solid particles are of a certain size distribution, the average size of the particles close to wall is larger than the particles away from the wall [10]. For the small particles, though they are easily carried by gas and their mean velocity is larger than that of large particles, many of them can not reach the wall before the large particles form a particle layer near the wall, and thereby locate closer to the center region (e.g., 10 mm away from the wall). Therefore, when particles are of a size distribution, the measured radial profiles of particle velocity are non-monotonic, especially in the section close to the cyclone inlet.

According to the results of Chan et al. [13], the near-wall particles' tangential velocity averaged over the length of the cyclone body was insensitive to the change of V_{in} and $C_{s,in}$. Based on our previous study [19], particles' average residence time in the cyclone is nearly constant at different V_{in} and $C_{s,in}$. Therefore, it is expected that the near-wall particles' axial velocity averaged over the length of the cyclone body is also inappreciably influenced by V_{in} and $C_{s,in}$. As introduced in previous section, $\bar{u}_s = 1.5$–2.5 m/s. For simplicity, $\bar{u}_s = 2$ m/s is proposed for the various V_{in} and $C_{s,in}$.

Table 2
Comparisons between measured and calculated l and G_s.

Experimental conditions	Measured				Calculated		Discrepancy (%)	
	$\bar{u}_s$ (m/s)	N_s	l (m)	G_s (kg/s)	l (m)	G_s (kg/s)	l	G_s
V_{in} = 17.4 m/s, $C_{s,in}$ = 4.51 kg/m^3	1.58	2.3	2.15	0.78	2.04	0.73	5.1	6.4
V_{in} = 25.3 m/s, $C_{s,in}$ = 5.06 kg/m^3	2.22	3.0	3.0	1.27	2.66	1.40	11.3	10.2

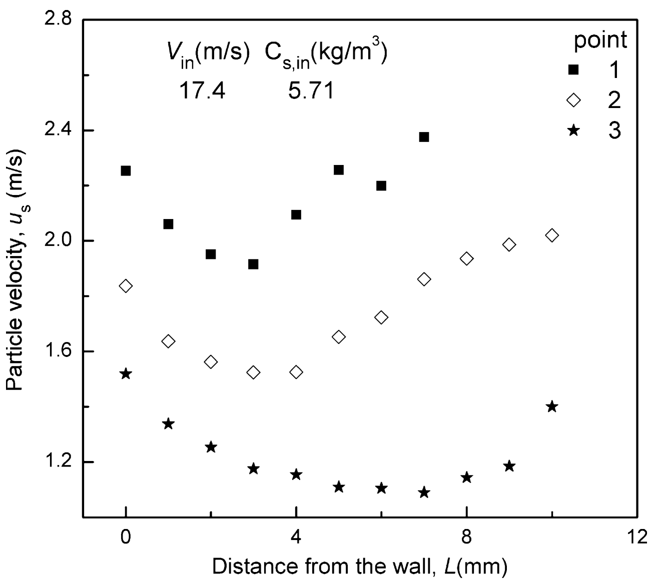

Fig. 8. Radial distributions of the particle velocity at different measuring points.

The radial profiles of u_s at Points 1, 2 and 3 when V_{in} = 17.4 m/s and $C_{s,in}$ = 5.71 kg/m^3 are shown in Fig. 8. It is clear that u_s decreases along the moving direction, indicating that the resistance on the near-wall particles is significant. The influences of V_{in} and $C_{s,in}$ on local velocity u_s need to be further investigated.

3.3. Geometrical characteristics of the spiral band

Fig. 9 shows the influence of V_{in} on the number of turns N_s. It can be seen that N_s increases with V_{in}, at the same time the travel distance of particles in the cyclone, l, increases and the particle bands' interval decreases. Since the particle average residence time in the cyclone is inappreciably affected by V_{in} [19], at a constant $C_{s,in}$, a larger N_s leads to more particle hold-up in the cyclone. If gas–solid reaction happens in the cyclone, it is more intensive.

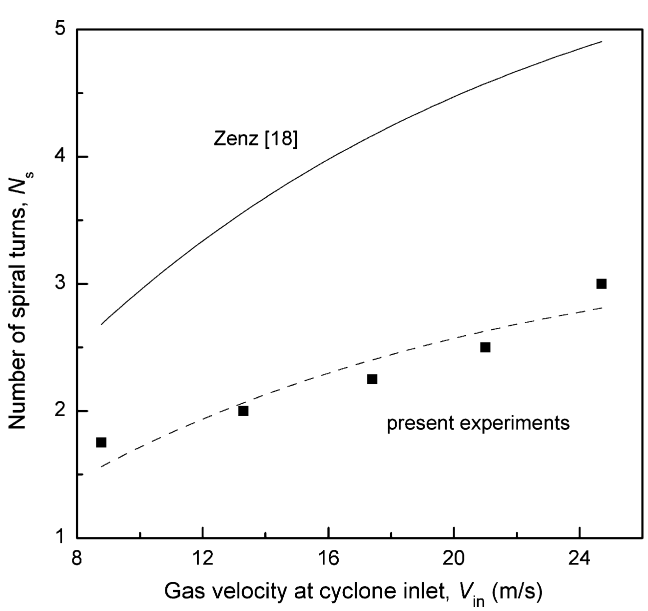

Fig. 9. Influence of inlet gas velocity on the number of turns of the particle band.

Zenz [18] summarized the relationship between N_s and V_{in} based on the experimental data. Against present experimental data, shown in Fig. 9, the correlation introduces an obvious over-prediction and is not applicable for the cyclone used in this study. The significant discrepancy may be caused by the different structure of the cyclones, and the structure effect on N_s needs to be further investigated.

The width of the spiral band is about 0.2–0.3 m in the present experiments, but the influence of operational parameters on the width is uncertain.

3.4. Validation of the measured data

The validation of the measured data is based on the internal relationship among the physical parameters. For example, the travel distance of the particles in the cyclone, l (m), on one hand can be estimated by multiplying particle average residence time $\bar{t}_r$ with $\bar{u}_s$, and on the other hand, it can approximately calculated by multiplying N_s with the perimeter of the cylinder [16,17]. Based on previous studies [19], $\bar{t}_r$ is approximately a constant of 1.36 s.

The measured volumetric solid concentration $C_{v,i}$ and particle velocity $u_{s,i}$ can be validated through the estimation of the circulating rate G_s. Approximately, in the cyclone, G_s can be estimated with Eq. (3), where, W is 0.3 m by experiments:

$$G_s = \sum_{i=1}^{k} l_t W \rho_r u_{s,i} C_{v,i} \tag{3}$$

As introduced in the experimental section, G_s can be directly measured in the experiments with hold-up method. The measured G_s's should be consistent with the calculated ones.

Table 2 shows the comparisons between measured results of l and G_s with the estimated ones. It can be seen the experimental measurements agree with the theoretical estimations well.

4. Conclusions

The distributions of volumetric solid concentration C_v and particle velocity u_s in the near-wall region of a cyclone were experimentally measured with fiber optical probes. The experimental results provide some new information for better understanding of the solid–gas flow and the estimation of solid–gas reaction inside the cyclone.

It was found that C_v distribution is severe non-uniform in the cross-section plane. Closer to the wall, C_v become higher. At a given position, C_v increases with the gas velocity or solid concentration at the cyclone inlet. Inside the cyclone, particles agglomerate into spiral bands with certain interval moving along the wall, downward to the dust hopper. The particle band in the cylindrical part of the cyclone is about 4–12 mm thick under present experimental conditions and along the moving bands, C_v increases.

The velocity of near-wall particles is in the range of 0.5–2.5 m/s. Its average value over the length of cyclone body is insensitive to the operation parameters and a mean value 2 m/s is proposed for particles in the near-wall region. The near-wall particle velocity decreases along the moving bands.

The number of spiral turns of particle band increases with the inlet gas velocity, but the dependency found by present experimental study was substantially different from the literature one. The discrepancy was suspected to be introduced by the cyclone structure. More investigations are suggested to be conducted in the future.

Acknowledgements

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