Dense-phase pneumatically conveyed coal particle velocity measurement using electrostatic probes and cross correlation algorithm

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Abstract. The fundamental measurement theory of an electrostatic probe and cross-correlation velocity measurement method are introduced in the paper. The effects of the probe’s geometric parameters including the length of the probe, the thickness, the length and the relative permittivity of the dielectric pipe, the radius of the screen on the dimensionless calibration coefficient ($k$) and the statistical error of the transit time ($\tau_m$) of the correlation velocity measurement system using electrostatic probes were investigated theoretically. Finally the measurement system was applied in a 10 mm bore horizontal section of a dense phase pneumatic conveying system under high pressure circulating pulverized coal over a superficial air velocity range of 0.5-7 m/s for a particle concentration 0.052-0.141 m$^3$/m$^3$. Experimental results obtained demonstrate that the system is capable of providing solid particle velocity measurements with repeatability better than 10% under the given experimental conditions.

1. INTRODUCTION

The measurement of gas-solid flow parameters is one of important research fields of multiphase flow, and is also an urgent problem needed to be resolved in fundamental theory, experimental investigation and industrial application of gas-solid flow. However due to the randomness of gas-solid interface in time and space the gas-solid flow characteristics and its measurement methods are far more complicated than single phase flow system. Although lots of research work has been done in the past decades, very few commercialized multiphase flowmeters are employed in industry today, and most of them are still under laboratory research and development. Among these flowmeters, the most promising have been the cross-correlation velocity measurement system which was developed in the 1960s. The non-obstructive measurement method has the advantages of broad measurement range and of good adaptability to hostile industrial environment. Wide ranges of sensing techniques including capacitive, ultrasonic and radiometric probes have been adopted. Useful results have been obtained from the measurement systems based on these probes, and successful applications for the non-contact, on-line continuous measurement of solid particle velocity in pneumatic transport system have been achieved (Xu L A. 1988, Thorn R. etal. 1982). In recent years, electrostatic sensing technique which is based on the particle charging of gas-solid two phase flows has created a major interest in the solid particle flow measurement because of its advantages over the other available correlation measurement techniques in good repeatability, high sensitivity, reliability and low cost (Boeck T. 1989, Yan Y. et al. 1995, Woodhead S. R and Amadi-Echendu J. E.1995, Ma J. and Yan Y. 2000, Gajewski J.B. 1996).
Boeck firstly applied ring shape electrostatic probes together with cross correlation techniques to measuring the particle velocity in a coal injection system, but few details on the measurement system and test results have been given (Boeck T. 1989). Yan and Coulthard studied the sensing mechanism, the spatial sensitivity and spatial filtering effects of the built-in electrostatic probes to optimize design and interpret signals (Yan Y. et al. 1995, Ma J. and Yan Y. 2000). And an electrostatic flow measurement system based on the probes was evaluated by theoretical analysis and by off-line experimental tests and pilot-plant trails. The results obtained showed that the measurement system achieves repeatability better than 2% and linearity within 12% over a velocity range 20-40 m/s for solid particle concentrations of in a range 0.01-0.44%. The correlation measurement systems using ring-shape electrostatic probes were also investigated by Woodhead (Woodhead S. R and Amadi-Echendu J. E. 1995) and Gajewski (Gajewski J.B. 1996), and the reasons for the measurement error of the systems were analyzed in detail.

Although some progress has previously been made on the use of the ring-shape electrostatic probes for metering gas-solid flow parameters, there are still some issues to be discussed, for example the effect of the length of the probe on its sensing characteristics was only considered in establishing its physical and mathematical model. Actually the geometric parameters of the probe including the thickness and relative permittivity of the dielectric pipe, the radius and length of the screen have important effect on the sensing characteristics of the probe, and thus the accuracy of the correlation measurement system based on the electrostatic probes. The objective of this paper is to analyze the effect of the length of the probe, the thickness, the length and relative permittivity of the dielectric pipe, the radius of the screen on the non-dimensional calibration coefficient and transit time of the correlation velocity measurement formula, and to provide the theoretical basis for the optimization design of the electrostatic probe. Presently, the reports on the application of the electrostatic probe is limited to dilute phase gas-solid flow such as the pulverized coal transport system with the particle concentration generally less than 0.5% in coal-fired power station. In recent years, dense phase pneumatic conveying technique, which has the advantages of lower energy consumption, lower wear and abrasion of pneumatic conveyor and higher solid to gas ratio by comparison with dilute phase conveying, has had widespread applications such as coal powder injection systems of blast furnaces in steel plants (Yang W. S et al. 2000) and pulverized coal transport of entrained flow gasifiers in chemical plants (Gong X and Guo X L. 2006). Similarly, it is essential for metering particle velocity of these dense phase pneumatic conveyors to minimize energy consumption and to control the transport of solid particles. Therefore a second objective of the paper is to evaluate a correlation velocity measurement system based on electrostatic probes on a bench-scale dense phase pneumatic conveying system under high pressure.

2. MEASUREMENT PRINCIPLE OF THE ELECTROSTATIC PROBE

During the pneumatic transport process of powder particles, the particles carry charges due to frictional contact charging between particles and the pipe wall and between particles and the airflow. The process of particle charging is complicated, the sign and amounts of charge carried by moving particles are dependent on many factors including particle size and shape, work functions, impurities, surface roughness, relative humidity, volume resistivity, permittivity, the contact energy between particles and pipe wall, the material and configuration of the pneumatic conveyor, and the transport conditions of particles in the pipeline, and hence the charging mechanism of pneumatically transported particles is not completely understood now. An electrostatic probe can be used to detect the charges carried by the moving particles. A number of different geometrical shapes of probes have been used as sensing elements for the flow measurement of solid particles in pipelines. Figure 1 shows some examples of the non-intrusive sensing arrangement. Among them, the ring shape probe has advantages of high sensitivity and can obtain the overall information of charged particles flow in its sensitive zone. Considering the precise layout and installation of the probe, and the operation safety of the dense phase pneumatic conveying system under high pressure, an outer electrostatic probe was adopted. The
electrostatic probe is enclosed in a measuring head illustrated in Figure 2. The probe is the main and most important part of the measuring head, whose construction is also described in details in the former works by Gajewski J.B. (Gajewski J.B. 1996). As shown in Figure 2, the length of the probe is denoted by $W$, the radius of the metal screen by $R_3$, the inner radius of the pipeline by $R_1$ and the outer radius by $R_2$, the length of the dielectric pipe by $l$ and its relative permittivity by $\varepsilon$. When the charged particles are distributed within the pipelines, the charge and potential are induced on the probe because of electrostatic induction. The total amount of the induced charge $q$ on it can be calculated by the following equation due to the axis-symmetry of the measuring head (Xu C L 2006, Xu C. L. and Wang S. M. 2008)

$$q(t) = \int [\sigma(z+vt, r) \cdot s(z, r)] dzdr$$

(1)

where $\sigma(z+vt, r)$, a random function due to the spatial and temporal distribution of the particles in the sensing zone, is the space charge distribution of the particles at $(z, r)$ in the sensing zone, and accordingly is also termed ‘electrostatic flow noise’; $s(z, r)$ is the spatial sensitivity distribution function, which is defined as the induced charge on the probe when a unity point charge is differently positioned at $(z, r)$ in the sensing zone of the probe.

![Fig. 1 Simplified diagram of non-intrusive electrostatic probes](image1)

![Fig. 2 Measuring head cross-sections of the ring-shape electrostatic probe](image2)

The electrostatic probe is connected to a preamplifier to amplify the induced signal, and the probe together with the preamplifier can be simplified as an equivalent circuit, schematically shown in Figure 3. According to Kirchhoff’s current law, the following expression applies

$$\frac{dq(t)}{dt} = C \frac{du_i(t)}{dt} + \frac{u_i(t)}{R}$$

(2)

where $u_i(t)$ is the input voltage of the preamplifier, $R=(R_e R_i)/(R_e+R_i)$, $C=C_e+C_i$, $C_e$ and $R_e$ are the equivalent capacitance and insulation resistance of the probe, and $C_i$ and $R_i$ are the equivalent input capacitance and input resistance of the preamplifier, respectively. Applying the Laplace transform to Equation (2) gives the following equation

$$\frac{U_i(s)}{Q(s)} = \frac{se^{sRC}}{1+se^{sRC}}$$

(3)

where $U_i(s)$ is the Laplace transform of $u_i(t)$ and $Q(s)$ is the Laplace transform of $q(t)$. 
If the condition $|sRC| << 1$ is fulfilled, and the initial induced charge on the electrostatic probe equals zero, the output signal of the probe can be expressed as:

$$u(t) = R \frac{dq(t)}{dt} = R \int \int \frac{d\sigma(z + vt, r)}{dt} \cdot s(z, r) dz dr$$  \hspace{1cm} (4)

From equation (4), it can be concluded that the output signal of the probe is the change of the induced charge/ the space charge distribution $\sigma(z + vt, r)$ with time, and is also a complicated random signal due to the random properties of electrostatic flow noise. In fact, the signal can not be predicted theoretically due to the unknown particle distribution, the non-uniform particle velocity profile and flow inhomogeneities in pneumatic transport pipelines. Therefore the above theoretical model of the probe only described its operation theory, and can not be directly compared with the experimental data obtained by the probe. Figure 4 shows the output signals of the probe when the particle with a unit charge moves along the axial direction at the different radial coordinates $r$. It can be seen that the signal nearby the pipe wall has larger amplitude and shorter duration time than the signal on the central axis of the probe.

$$Fig. 4 \hspace{1cm} \text{Theoretical output current of the electrostatic probe from a unit charge traveling through the probe with } v=1 \text{ m/s}$$

### 3. CORRELATION VELOCITY MEASUREMENT PRINCIPLE AND MEASUREMENT ERROR ANALYSIS

#### 3.1 Correlation velocity measurement principle

A block diagram of the flowmeter using electrostatic probes is shown in Fig. 5. In the velocity measurement, the actually measured parameter is the flow transit time $\tau_m$ determined by cross correlating the two signals derived from the upstream and downstream probes. The correlation velocity $v_c$ is then calculated from $\tau_m$ and the known probe separation $L$

$$v_c = \frac{L}{\tau_m} \hspace{1cm} (5)$$
The mean velocity of particles, $v_m$, in pneumatic pipelines can be calculated by

$$v_m = \frac{\int\int v(x,y)c(x,y)dxdy}{\int\int c(x,y)dxdy}$$  \hspace{1cm} (6)

where $v(x,y)$ and $c(x,y)$ are the particle velocity and concentration profile, respectively.

If the unknown particle distribution, the non-uniform particle velocity profile, non-linear sensing characteristics of the electrostatic probe and flow inhomogeneities in pneumatic transport pipeline are taken into account, a discrepancy exists between the correlation velocity $v_c$, and the mean particle velocity $v_m$. The relationship between $v_c$ and $v_m$ can be expressed as

$$v_m = k L/\tau_m$$  \hspace{1cm} (7)

where $k$ denotes dimensionless calibration coefficient, whose instability, to a large extent, influences the measurement accuracy of $v_m$. The correlation properties between the upstream and downstream probes and the systematic error ($\Delta L/L$) should be considered when determining the physical probe spacing $L$. The reasons are that the larger probe space results in the decrease of cross correlation coefficient of the output signal of the two probes, and contrarily the larger systematic error ($\Delta L/L$) results from the electrical field interaction between the probes. Beck suggested the range of the probe spacing $L$ (Beck M S and Plaskowski A. 1987):

$$L = (1/2~2)D$$  \hspace{1cm} (8)

where $D$ is the pipeline diameter. The systematic error ($\Delta L/L$) could be corrected by calibrating the sensing head using a small-scale insulated hell conveyor with a known and uniform speed (Keech R P. 1982). The geometric parameters of the electrostatic probe affect $k$ and $\tau_m$ in complex ways, and hence the measurement error of the mean particle velocity. These will be discussed in the following sections.

### 3.2 The effect of the geometric parameters of the electrostatic probe on $k$

The effects of the length of the built-in electrostatic probe and particle velocity profile on $k$ were analyzed in (Yan Y. et al. 1995). Actually the geometric parameters of the outer electrostatic probe including the length of the probe, the thickness, and the length and relative permittivity of the dielectric pipe, the radius of the screen have influence on its sensitivity distribution, and hence the accuracy of correlation velocity measurement. The correlation velocity depends upon the total contributions of all the stream lines through the sensing system. Each stream line velocity $v(x,y)$ will be weighted by the spatial sensitivity, correlation coefficient, and concentration of solid particle at that stream line $(x, y)$ (Yan Y. et al. 1995), that is

$$v_c = \frac{\int\int v(x,y)s(x,y)\rho(x,y)c(x,y)dxdy}{\int\int s(x,y)\rho(x,y)c(x,y)dxdy}$$  \hspace{1cm} (9)

where $s(x,y)$ is the spatial sensitivity distribution related to the geometric parameters of the electrostatic probe; $\rho(x,y)$ is the stream line correlation coefficient, which relates not only to the
geometry and dimensions of the sensing head (spatial filtering properties and probe spacing), but also to the flow characteristics and to the operating principles of the signal processing electronics and cross correlation algorithm. For simplification, on the assumption that $\rho(x, y)$ is constant, it can be concluded from equation (9) that $v_c$ can truly represent $v_m$ if sensitivity distribution $s(x, y)$ is uniform, that is, $k = 1$. Figure 6 shows the sensitivity distribution of the electrostatic probe with the lengths being 3 mm, 5 mm and 7 mm, respectively. It can be seen that the length of the probe is one of important factors influencing the spatial sensitivity distribution. The more homogeneous sensitivity distribution attributes to the longer probe. The higher sensitivity exists nearby the pipe wall, which illustrates the probe is more sensitive to the particle adjacent to the pipe wall. Additionally, other geometric parameters of the probe also have important effect on the sensitivity distribution (Xu C. L. and Wang S. M. 2007). Therefore the non-uniformity of the spatial sensitivity distribution $s(x, y)$ can be reduced by optimizing the geometry of the electrostatic probe.

![Fig. 6 Sensitivity distribution of the electrostatic probe with different lengths](image)

As far as the gas–solid two-phase flows are concerned, the interaction at the gas–solid phase interface leads to larger variations in particle velocity distribution at different locations of transport pipes. Even in the steady flow condition, the particle concentration and velocity distribution are non-uniform. As a consequence, the gas–solid two-phase flow process is very complicated and, presently, it is impossible to obtain a general solution of the distribution profiles. To simplify the analysis of the effect of the geometric parameters of the probe and particle distribution profile on $k$, it is assumed that the particle velocity profile is axisymmetrical and obeys a power-law model (Yan Y. et al. 1995)

$$v(x, y) = v(r) = v_{\text{max}} \left(1 - \frac{r}{R}\right)^n$$  \hspace{1cm} (10)

where $v_{\text{max}}$ is the particle velocity at the axis of the transport pipe, $n$ is the exponent of the power model, indicating the profile shape of particle velocity distribution over the cross-section of a pneumatic transport pipeline, and this is related to the roughness of the pipe and the Reynolds number.

On the assumption that particle concentration $C(x, y)$ is constant over the cross-section of the pipe, the mean velocity of particles $v_m$ can then be calculated by

$$v_m = \frac{2n^2}{(n+1)(2n+1)} v_{\text{max}}$$  \hspace{1cm} (11)

Similarly, correlation velocity can be expressed as

$$v_c = \frac{\int \int C(x, y)v(x, y)\rho(x, y)s(x, y)dx dy}{\int \int C(x, y)\rho(x, y)s(x, y)dx dy} \frac{\int \int r v(r)s(r)dr}{\int \int r s(r)dr}$$  \hspace{1cm} (12)

Combining equations (10), (11) and (12), the dimensionless calibration coefficient $k$ can be expressed as
From equation (13), \( k \) can be calculated using numerical methods because the spatial sensitivity \( S(r) \) is known for a given electrostatic probe. The charge induced on the ring-shaped probe with different geometric sizes from a single particle having a unity charge was modeled mathematically in (Keech R P. 1982, Xu C. L. and Wang S. M. 2007, Xu C. L. and Wang S. M. 2007), and the spatial sensitivity distribution of the probe was analyzed using finite element method. On the above basis, the effect of the geometric parameters of the sensing head on the dimensionless calibration coefficient \( k \) will be further investigated. In the numerical calculation, the radius of the dielectric pipe \( R_1 \) equals to 5 mm.

### 3.2.1 The effect of the length of the probe on \( k \)

Fig. 7 shows the variation of \( k \) with particle velocity profiles when the probe lengths \( W_e \) are 3 mm, 5 mm, 7 mm and 20 mm, respectively. And the other parameters of the measuring head are kept at \( R_2=10 \text{ mm}, \ l=15 \text{ mm}, \ \epsilon =3.75 \text{ and } R_3=18 \text{ mm} \). If the velocity profile is unknown, a constant calibration coefficient may have to be used. In this case, the average value of \( k \) over the practical range of velocity profiles should be taken. When the value of \( n \) varies in the range 4-12, it is estimated that the relative change in \( k \) (\( \Delta k/k \)) is 1.09% for \( W_e=3 \text{ mm} \), and 0.29% for \( W_e=20 \text{ mm} \). It can be concluded that the dimensionless calibration coefficient is not constant for a probe with a given length, and the longer probe contributes to reduce the effect of velocity profiles on \( k \).

![Fig. 7 Variation of \( k \) with particle velocity distribution for different probe lengths](image)

### 3.2.2 The effect of the permittivity of the dielectric pipe on \( k \)

Fig. 8 shows the variation of \( k \) with particle velocity profiles when the relative permittivity of the dielectric pipe \( \epsilon \) is 1, 4, 6, 8 and 12, respectively. And the other parameters of the measuring head are kept at \( W_e=5 \text{ mm}, \ R_2=10 \text{ mm}, \ R_3=18 \text{ mm} \text{ and } l=15 \text{ mm} \). It is estimated that the relative change in \( k \) with the variable velocity profile \( n \) being in the range 4-12 is not greater than 1.07% for the relative permittivity of the dielectric pipe \( \epsilon=1\sim12 \).
3.2.3 The effect of the thickness of the dielectric pipe on $k$

Fig. 9 shows the variation of $k$ with particle velocity profiles when the thicknesses of the dielectric pipe ($R_2-R_1$) are 3 mm, 5 mm, 8 mm and 10 mm, respectively. And the other parameters of the measuring head are kept at $W_e=5$ mm, $\varepsilon=3.75$, $R_3=18$ mm and $l=15$ mm. When the value of $n$ varies in the range 4-12, it is estimated that the relative change in $k$ ($\Delta k/k$) is 1.29% for $R_2-R_1=3$ mm, and 0.89% for $R_2-R_1=10$ mm. Therefore it can be concluded that the thicker dielectric pipe contributes to reduce the effect of velocity profiles on $k$.

3.2.4 The effect of the length of the dielectric pipe on $k$

Fig. 10 shows the variation of $k$ with particle velocity profiles when the lengths of the dielectric pipe $l$ are 10 mm, 15 mm, 20 mm and 25 mm, respectively. And the other parameters of the measuring head are kept at $W_e=5$ mm, $R_2=10$ mm, $\varepsilon=3.75$ and $R_3=18$ mm. When the value of $n$ varies in the range 4-12, it is estimated that the relative change in $k$ ($\Delta k/k$) is 1.67% for $l=10$ mm, and 0.67% for $l=25$ mm. This implies that the longer dielectric pipe contributes to reduce the effect of particle velocity profiles on $k$. 
3.2.5 The effect of the radius of the screen on $k$

Fig. 11 shows the variation of $k$ with particle velocity profiles when the radiiuses of the screen are 14 mm, 18 mm and 22 mm, respectively. And the other parameters of the measuring head are kept at $W_x=5$ mm, $R_x=10$ mm, $c=3.75$ and $l=15$ mm. It is estimated that the relative change in $k$ with the variable velocity profile $n$ being in the range 4-12 is almost constant (1.07%), which illustrates that the radius of the screen has no effect on the dimensionless calibration coefficient $k$. But it should be noted that the variation of particle velocity profiles causes the relative change in $k$.

3.3 The effect of the geometric parameters of the electrostatic probe on $\tau_m$

Statistical error exists in estimating the transit time $\tau_m$ from equation (7) due to the randomness of the electrostatic flow noise. The standard deviation $\sigma(\tau_m)$ of the transit time measurement is dependent on the output signal bandwidth of the electrostatic probe ($B$), correlation integration time ($T$), and the correlation coefficient ($\rho_m$) (Yan Y. et al 1995, Beck M S and Plaskowski A. 1987)

$$\sigma(\tau_m) = \left[ \frac{0.038}{TB^{1.5}} \left( \frac{1}{\rho_m^2} - 1 \right) \right]^{1/2}$$

(14)

From equation (14), the standard deviation is proportional to $B^{-1.5}$, which means that a little change in the signal bandwidth $B$ may cause the larger standard deviation. Therefore the electrostatic probe should be carefully designed to extract the information of the electrostatic flow noise in a larger frequency bandwidth.

The frequency response characteristics of the measurement system are determined by both the spatial filtering effect of the probe and the preamplifier connected to the probe. The frequency
response characteristics can be theoretically expressed as (Xu C. L 2006, Xu C. L. and Wang S. M. 2008):

\[
\left| U_1(f) \right| = 2\pi R \left( \frac{a\sqrt{\pi}}{v\sqrt{b}} \exp\left( -\frac{(\pi f)^2}{bv^2} \right) + \frac{c\sqrt{\pi}}{v\sqrt{d}} \exp\left( -\frac{(\pi f)^2}{dv^2} \right) \right)
\]

(15)

where \(a, b, c, d\) are the constants related to the geometric parameters of the measuring head and the radial position \(r\) of the point charge in the sensing zone, \(v\) is particle velocity, and \(f\) is frequency. From equation (15), the frequency response characteristics of the measurement system are dependent on the geometry of the measuring head and particle velocity. From the literatures (Xu C. L. and Wang S. M. 2007, Xu C. L. and Wang S. M. 2007, Xu C. L., Zhao Y. and Wang S. 2006), compared with the relative permittivity of the dielectric pipe \(\varepsilon\) and the inner radius of the screen \(R_3\), the length and thickness of the dielectric pipe and the length of the probe have important effect on the sensitivity distribution of the electrostatic probe, and hence the constants \(a, b, c, d\) and the bandwidth of the measurement system. In the paper, on the basis of the probe’s mathematical and finite element model established in (Xu C. L. and Wang S. M. 2007, Xu C. L. and Wang S. M. 2007), the effects of these factors \((l, R_2-R_1, W_e)\) on the bandwidth of the probe are investigated numerically using finite element method. In the numerical simulations, other parameters of the measuring head are kept at \(\varepsilon=3.75, R_1=5\) mm and \(R_3=18\) mm, and particle velocity \(v\) is 10 m/s.

3.3.1 The effect of the length of the electrostatic probe on the bandwidth

Fig.12 shows the effect of the length of the electrostatic probe on the bandwidth \((B)\) of the measurement system. The lengths \(W_e\) are 3 mm, 5 mm and 10 mm, respectively. And the other parameters of the measuring head are kept at \(R_2=10\) mm and \(l=15\) mm. From Figure 12, it can be seen that the bandwidth decreases with the increase of the length of the probe nearby pipe wall \((r=4.5\) mm\)), whereas there is almost no change on the central axis of the probe. This means that the shorter probe attributes to the reduction of the standard deviation \(\sigma(\tau_m)\) of the transit time measurement.

3.3.2 The effect of the thickness of dielectric pipe on the bandwidth

Fig.13 shows the effect of the thickness of the dielectric pipe on the bandwidth \((B)\) of the measurement system. The thicknesses \((R_2-R_1)\) are 3 mm, 5 mm, 8 mm and 10 mm, respectively. And the other parameters are kept at \(W_e=5\) mm and \(l=15\) mm. It can be seen that the bandwidths decrease with the increase of the thickness and then approach constants nearby pipe wall, and on the central axis of the probe.
3.3.3 The effect of the length of the dielectric pipe on the bandwidth

Fig. 14 shows the effect of the length of the dielectric pipe on the bandwidth ($B$) of the measurement system. The lengths ($l$) are 10 mm, 15 mm and 20 mm, respectively. And the other parameters of the measuring head are kept at $W_e=5$ mm and $R_2=10$ mm. From Figure 14, it can be seen that the bandwidths rapidly decreases with the increase of the length of the dielectric pipe nearby pipe wall ($r=4.5$ mm) and on the central axis of the probe ($r=0$ mm), which means that the longer dielectric pipe results in the increase of the standard deviation $\sigma(\tau_m)$ of the transit time measurement.

From the results of the sections 3.2 and 3.3, we know that the shorter electrostatic probe not only increases the signal bandwidth ($B$) of the probe, and improves the statistical error ($\sigma(\tau_m)$) of the transit time, but also reduces the uncertainty of the probe space. But it should be noted that the shorter electrostatic probe leads to the non-uniformity of the sensitivity distribution, which largely influences the stability of the dimensionless calibration coefficient $k$. The thicker dielectric pipe is useful for the uniformity of the sensitivity distribution, and reduces the effect of particle velocity profiles on the dimensionless calibration coefficient $k$, but the thicker pipe also reduces the signal bandwidth of the probe, and hence increases the statistical error of the transit time. The longer dielectric pipe results in the similar change in the measurement system to the thicker pipe. Therefore the non-uniformity of the sensitivity distribution and the signal bandwidth of the probe should be synthetically taken into consideration when optimizing the geometry of the electrostatic probe used in a correlation velocity measurement system. Additionally, particle velocity is also an important factor influencing the signal bandwidth of the probe, and the higher velocity produces the wider bandwidth (Xu C. L., Zhao Y. and Wang S. 2006). Hence the statistical error of the transit time will be reduced at the high velocity.

4. EXPERIMENTAL RESULTS AND DISCUSSION
4.1 Experimental rig

A planar view of the main apparatus layout is shown in Fig. 15. The constituent components of the apparatus and their functions are as follows:

- The volume capacity of the hoppers (3) is $0.648 \, \text{m}^3$, and by switching the valves in pipelines, the hoppers two can be used to feed and receive powder particles respectively.
- Transport pipeline section consists of a $53.4 \, \text{m}$ of $\Phi16 \times 3 \, \text{mm}$ bore stainless steel pipe.
- Nitrogen cylinder group (8) supplies the transport gas for the dense phase conveyor, and nitrogen exhausted from the pipeline section passes first through the receiving hopper, where bug dust collector is used to disengage the solid particles from the nitrogen flow. The clean nitrogen then passes through a rotor meter (13) to facilitate the measurement of gas flowrate before passing through the electrical control valve (1) to atmosphere. The operating pressure of the receiving hopper can be adjusted by the control valve.
- A computerized data acquisition system (not shown) allowed the signals from all of the probes to be logged simultaneously and saved for further processing. The probes included a weighing cell (2) for the measurement of particle mass in a time interval, 3 rotor meters (10-12) for the measurement of transport nitrogen flowrate, 3 pressure transducers and two electrostatic probes (9).

![Fig. 15 Schematic diagram of Dense-Phase Pneumatic Conveying System of Pulverized Coal](image)

The high-pressure nitrogen first passes through the gas buffer tank (7) and then is divided into two ways. The one forms fluidizing gas (5), which first fluidizes the powder particles in the feeding hopper, then carries the fluidized particles passing through the transport pipeline, and finally enters the receiving hopper. The other is used to keep the pressure of the feeding hopper (termed keeping pressure gas (6)) and to change the solid gas mass ratio in the transport pipeline (termed supplement gas (4)). The supplement gas is also called secondary gas.

The correlation velocity measurement system consists of the measuring head, preamplifiers and a computer-based data acquisition system. The output signals of the probes are amplified by the preamplifiers, then are sampled, saved and analyzed by the computer. The sampling rate was 1330 Hz. The geometric parameters of the measuring head are kept at $R_1=5 \, \text{mm}$, $R_2=10 \, \text{mm}$, $l=100 \, \text{mm}$, $e_i=3.75$. 


and $R_3=18\text{ mm}$. The length of the electrostatic probe is 4 mm, and the probe space is 40 mm. The measuring head was installed at the outlet of the horizontal pipeline section with the distance being 15 m from the feeding hopper. The conveyed material is pulverized bituminous coal, whose characteristic parameters are listed in table 1. Fig. 16 shows the coal particle size distribution histogram measured by Centrifugal Particle Size Analyzer (SA-CP3, SHIMADZU). During the experiments, the conveying gas is $N_2$ with a maximum pressure of up to 4.8 Mpa, and particle concentration is in a range of 5.2-14.1% $\text{m}^3$/m$^3$. The particle concentration $\beta_s$ in pipelines can be estimated using the following Equation

$$\beta_s = \frac{Q_s}{Q_a + Q_s} \times 100\%$$  \hspace{1cm} (16)

where $Q_a$ is the volumetric flowrate of the pulverized coal with the relation $Q_a = \frac{M_s}{\rho_s}$. $\rho_s$ denotes the particle density and $M_s$ is the coal mass flowrate, which is obtained by weighing the amount of the solid particle collected from the receiving feeder in a suitable time interval.

| Material | Mean diameter $d_s$ (µm) | Density $\rho_s$ (Kg/m$^3$) | Shape factor $\Phi_s$ |
|----------|--------------------------|-----------------------------|----------------------|
| Coal     | 35.6                     | 1350                        | 0.63                 |

Table 1 Characteristic parameters of bituminous coal particles

Fig.16 Coal particle size distribution histogram

4.2 Results and Discussion

Due to the lack of the calibration instrumentation for gas-solid flow measurement, the superficial gas velocity is only a traceable reference with which the measured particles mean velocity is compared. The superficial gas velocity $v_s$ can be calculated by

$$v_s = \frac{Q_a}{A}$$  \hspace{1cm} (17)

where $Q_a$ is the volumetric flowrate of transport nitrogen. $A$ is the cross section area of transport pipeline.

The paper adopted the generalized cross correlation algorithm to estimate the transit time $\tau_m$, which can effectively restrain the effect of the noise on the estimation, and improve the accuracy of the transit time measurement. Throughout the entire velocity and concentration ranges of the experimental rig the correlation algorithm gave clearly defined correlogram peaks. A typical correlogram together with its waveforms of the raw signals from the electrostatic probes were recorded during the tests and are shown in Fig. 17. Under all flow conditions, the correlation coefficient representing the similarity between upstream and downstream signals is 0.20-0.40. This suggests that the dense phase gas-solid
flow exhibits unsteady flow regime, particle velocity and concentration profiles over the pipe’s cross sectional area.

Fig. 17 A typical correlogram and its raw signals at correlation velocity 0.8 m/s

Fig. 18 shows the comparison between the correlation velocity \( v_c \) and superficial gas velocity \( v_a \). The correlation velocity is an average of consecutive ten measurements. Over a velocity range of 0.5 - 7 m/s for a particle concentration range 0.052-0.141 m\(^3\)/m\(^3\), the measured velocities are slightly higher than the superficial gas velocities. Several reasons for the phenomenon may be found. Firstly, the higher particle concentration over the cross section of the pneumatic pipeline results in the reduction of the area occupied by the transport gas, and the particles are prone to accumulate within the horizontal pipeline due to their intrinsically adhesive properties and own gravities. As a consequence, if the total particle concentration \((\beta)\) is considered, the true gas velocities should be estimated using the following Equation

\[
v_a = \frac{Q_a}{A(1 - \beta)} \tag{18}
\]

From Equation (18), it can be concluded that the true gas velocities are higher than the calculated superficial ones because of the reduced effective cross sectional area of the gas flow. Particle size is an important factor influencing the slip between the particles and the gas flow, and Klinzing’s studies showed that the slip velocity is almost proportional to the particle size (Klinzing, 1987). In our experiments, the mean size of pneumatically conveyed particles is 35.6 \( \mu m \), and thus they have better following characteristics. Therefore it is possible that particle velocities are higher than the superficial ones. Secondly, the velocity distribution in the lower section of the horizontal pneumatic pipeline is relatively flat due to the higher particle concentration, but the particle concentration and velocity distribution are exactly reverse in the upper section of the pipeline. The electrostatic probe has non-linear sensing mechanism that is more sensitive to the particle closest to the pipe wall. This means that the particles nearer to the probe are giving a higher weighting factor on the final average velocity reading. Hence the upper particle velocity attributes to the higher measured correlation velocity. Finally the particle concentration profile of the dense phase pneumatic pipeline fluctuates continuously due to the instability of the dense phase gas-solid flow (Liang C., Zhao C. S. and Chen X. P. 2007),
which leads to a large change in particle velocity and hence the higher data scattering of the correlation velocity measurement. Although the accuracy of the particle measurement velocity using the spatial filtering method can not be determined due to the lack of the calibration instrumentation and equipment, its repeatability error within ±10% is verified by the experiments under the given experimental conditions. It must be stressed that, since the data in Fig.18 combine both the repeatability of the correlation velocity measurement system and the stability of the solids velocity in the pipeline, the actual repeatability of the system is better than 10%.

Fig.18 Comparison between the correlation velocity and $v_o$

5. CONCLUSIONS

The effects of the probe’s geometric parameters including the length of the probe, the thickness, the length and the relative permittivity of the dielectric pipe, the radius of the screen on the dimensionless calibration coefficient ($k$) and the statistical error of the transit time ($\tau_m$) of the correlation velocity measurement system using electrostatic probes were investigated, which provides theoretical basis for the optimization design of the electrostatic probe. Due to the lack of the calibration instrumentation for gas-solid flow measurement, the reference in the experiments is the superficial air velocity with which the measured correlation velocity is compared. Experimental results on a pilot dense phase pneumatic conveying rig of pulverized coal under high pressure indicate that the correlation method is capable of making particles mean velocity measurement with repeatability better than ±10% over a velocity range of 0.5 - 7 m/s for a particle concentration range of 0.052-0.141 m$^3$/m$^3$.

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