Modelling and calibration of a Ring-shaped Electrostatic Meter

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Abstract. Ring-shaped electrostatic flow meters can provide very useful information on pneumatically transported air-solids mixture. This type of meters are popular in measuring and controlling the pulverized coal flow distribution among conveyors leading to burners in coal-fired power stations, and they have also been used for research purposes, e.g. for the investigation of electrification mechanism of air-solids two-phase flow. In this paper, finite element method (FEM) is employed to analyze the characteristics of ring-shaped electrostatic meters, and a mathematic model has been developed to express the relationship between the meter’s voltage output and the motion of charged particles in the sensing volume. The theoretical analysis and the test results using a belt rig demonstrate that the output of the meter depends upon many parameters including the characteristics of conditioning circuitry, the particle velocity vector, the amount and the rate of change of the charge carried by particles, the locations of particles and etc. This paper also introduces a method to optimize the theoretical model via calibration.

1. INTRODUCTION

In coal-fired power station, coal has to be pulverized and pneumatically conveyed to burners. The solid to air ratio in term of mass is usually less than 1.5:1 (Coulthard, J et al., 1998 ), the equivalent volumetric concentration is less than 0.05% (at 100 ° C). This characterizes the typically dilute (lean) flow. The concentration is so low that the sensors based on the acoustic, microwave and capacitive principles may not be sensitive enough for practical applications, whilst the electrostatic technique appears to have advantages in this aspect (J Y Zhang., 2005; Zhang Bo et al., 2007). Electrification occurs due to the collision, friction and the separation between particles, and between particles and the pipe wall (Bailey, A, G et al., 1993; Armour-Chelu D I et al., 2002; Nifuku M,Sasaki T et al., 1989) in the milling or pulverizing and the pneumatic conveying processes. The electrostatic ring-shaped air solids flow meters are non-intrusive, fast responding, installation-easy and maintenance free. With its high sensitivity, it seems that this type of meters is more suitable for applications under the dilute conditions (Kleber W et al., 1998; Gajewski J B et al., 2006; Chuanlong Xu et al., 2008).

Electrostatic meter can be used to measure the flow distributions and velocities among pipes leading to a boiler and to indicate the average size of particles. It can also be used to for on-line and real-time monitoring the conditions of the milling and transportation systems by indicating
the instability and malfunctioning to predict and prevent severe problems such as blockage.

Such a meter can provide the on-line continuous feedback information for closed-loop control so that the air to solids ratio can be optimized to reduce emissions and improve efficiency (Zhang J Q et al., 2003).

This paper analyses the spatial sensitivity field of the ring-shaped electrostatic meter and establishes a mathematic model expressing the relationship between the meter’s output voltage, particle velocities and the amount of charges carried by particles using Finite Element Method (FEM). This paper also demonstrates how a mathematic model can be optimized via the calibration which was carried out at the laboratory of the University of Teesside, U.K. using a 40mm diameter ABB electrostatic meter, trade marked Pfmaster as a part of work for an EU funded project (J Y Zhang et al., 2008).

2. ELECTROSTATIC METER AND EQUIVALENT CIRCUIT

Fig. 1 shows the sectional view of a ring shaped electrostatic sensor, which comprises of a short spool piece and a ring electrode (probe) with the surrounding insulator. The ring electrode is mounted flush with the inner pipe wall offering non-intrusive measurement. Usually the metal pipe is earthed so that it acts as the electrostatic screen and also as the signal reference (signal ground) of the conditioning circuit input.

![Fig. 1 Sectional View of ring-shaped electrostatic Sensor](image)

Based on electrostatic induction theory, a certain amount of charge \( Q \) is induced on the electrode when charged particles are distributed among the sensing zone. The signal is amplified by the conditioning circuit which is usually a charge amplifier. The simplified equivalent circuit is shown in Fig. 2. According to Kirchhoff’s current law, the relationship between the induced charge and the potential on the electrode is given by,

\[
\frac{dQ(t)}{dt} = C \frac{dU_i(t)}{dt} + \frac{U_i(t)}{R} \quad (1)
\]

\( U_i(t) \) is the input voltage of the conditioning circuit \( R = (R_a R_i) / (R_a + R_i) \); \( C = C_a + C_i + C_c \), where \( C_a \) and \( R_a \) are the capacitance of the electrode and insulation leakage resistance respectively. \( C_c \) is the stray capacitance of the cables connecting the electrode to the charge amplifier. \( C_i \) and \( R_i \) are the input capacitance and resistance of the conditioning circuit, including the equivalent capacitance and resistance in the feedback path of the charge amplifier due to the Miller effect. The Laplace transform and the Fourier transforms of equation (1) are given by,

\[
\frac{U_i(s)}{Q(s)} = \frac{sR}{1 + sRC} \quad \frac{U_i(j\omega)}{Q(j\omega)} = \frac{j\omega R}{1 + j\omega RC} \quad (2)
\]

Here \( U_i(s) \) and \( Q(s) \) are the Laplace transform of \( U_i(t) \) and \( Q(t) \), \( s \) the Laplace operator. \( U_i(j\omega) \)
and $Q(j\omega)$ are the Fourier transforms of $U_i(t)$ and $Q(t)$, $\omega$ the angular frequency.

The sensor will behave differently under the following three different conditions.

1. $|j\omega RC| << 1$, then equation (2) can be simplified as,

$$U_i(j\omega) = j\omega Q(j\omega) \quad (3)$$

Assuming the zero initial condition, the time-domain analysis of equation (3) is,

$$U_i(t) = R \frac{dQ(t)}{dt} \quad (4)$$

Which indicates the output voltage of the charge amplifier is proportional to the induced currents.

2. $|j\omega RC| >> 1$,

$$U_i(j\omega) = Q(j\omega)/C \quad (5)$$

Time-domain analysis to equation (5) can be expressed as,

$$U_i(t) = Q(t)/C + C' \quad (6)$$

Ignoring $C'$, the integral constant, it can be seen that the output voltage of the charge amplifier is proportional to the charge induced on the electrode and inversely proportional to the equivalent capacitance.

3. If $|j\omega RC|$ is comparable with 1, based on equation (1), we have,

$$U_i(t) = e^{-\frac{1}{RCt}} \left[ \frac{1}{RC} \int Q(t)dt + C' \right] \quad (7)$$

Which indicates the input voltage of the operational amplifier is determined by both the induced charge and its integration value. $C'$ stands for the integration constant.

In practice, the equivalent capacitance C is high primarily due to the Miller effect, the condition $|j\omega RC| >> 1$ can usually be met. However in a dynamic electrostatic sensor, only AC signal components are selected by using a high pass filter with a very low lower cut-off frequency (a practical differentiator with low inertia).

![Fig. 2 The equivalent circuit of electrostatic sensor](image)

Therefore the output of the meter can be expressed as

$$U_o(t) = k \frac{du_i(t)}{dt} = k \frac{1}{C} \frac{dQ(t)}{dt} = k \frac{1}{C_F} \frac{dQ(t)}{dt} \quad (8)$$

Where $k$ is a proportional factor determined by the gain of the entire conditioning circuit, $C_F$ is the feedback capacitance of the charge amplifier, $U_o(t)$ the output of the sensor.
3. MATHETICAL MODELING

Assuming the magnetic field due to the moving charged particles can be ignored, the electrostatic equilibrium system mentioned above is governed by

$$\nabla \cdot [\varepsilon(x, y, z) \nabla \phi(x, y, z)] = -\rho(x, y, z)$$

$$\phi(x, y, z)_{|\Gamma_p} = 0$$

$$\phi(x, y, z, t)_{|\Gamma_e} = \frac{1}{C} Q(t)$$

$$E_{\infty} = 0$$

\[ (9) \]

Where $\phi(x, y, z)$ is the potential distribution inside the region; the boundary $\Gamma_p$ represents the grounded pipeline wall with zero potential value, $\Gamma_e$ is the ring electrode which is connected to the conditioning circuitry. $\rho(x, y, z)$ is the charge density distribution; $\varepsilon_0$ is dielectric constant in vacuum, $\varepsilon(x, y, z)$ denotes the relative permittivity distribution of the powder material, $E_{\infty}$ is the electric field strength at the infinite distance.

Considering the complexity of gas-solids flow, the flow pattern or particulate material distribution is capricious, the analytical solution to equation (9) can hardly be found. FEM can be used to obtain a numerical solution to equation (10), which is the equivalent form to equation (9) with the same boundary conditions.

$$F(\phi) = \int \left[ \frac{\varepsilon}{2} \left( \frac{\partial \phi}{\partial x} \right)^2 + \left( \frac{\partial \phi}{\partial y} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right] - \rho \phi dx dy dz$$

\[ (10) \]

The charge induced on the ring electrode varies with the fluctuations of quasi-static electric field which is produced by the moving charged particles. In the column coordinate system, it can be expressed as,

$$Q(t) = \iiint \delta(r, \theta, z, t) s(r, \theta, z) d\Omega$$

\[ (11) \]

where $\Omega_e$ denotes the sensing zone of the electrode. Due to the uncertainty of the charge distribution of particles, the electrostatic charge noise $q(r, o, z, t)$ is a stochastic variable function of time. $s(r, o, z)$ is the space sensitivity distribution function. From equation (11), the induced charge $Q(t)$ on the electrode is the weighted average of $q(r, o, z, t)$ by $s(r, o, z)$ which can be found using FEM mentioned above.

Due to the symmetrical axial geometry of the sensor, the induced charge on the ring electrode by the point charge at different angular position $o$ in the same circumference is equal. So that the spatial sensitivity does not vary with $o$, the angular coordinate. Hence $s(r, o, z) = s(r, z)$. The simulation calculation can be implemented in the rectangular region as depicted in figure 3. The origin ($z=0$, $r=0$) is at the geometrical centre of the sensor. The diameter and width of the sensor for the simulation is 200mm and 2mm respectively to match the dimensions of the sensor used for the experiments.
For the given radial positions \( r = 0, 30 \text{mm}, \text{and} r = 80 \text{mm} \), \( s(r,z) \) decreases with the increase of axial location \( z \) which can be seen in Fig. 4(a). It can also be seen that the variation of \( s(r,z) \) with the radial coordinate \( r \) depends on the axial location \( z \), e.g. at \( z = 50 \text{mm} \), \( s(r,z) \) first slowly increases with \( r \) and then decreases with \( r \) when \( r \) approaching the value of pipe radius shown in Fig. 4(b). This is due to the fact that the spatial angle included between the charged particle source to the ring electrode varies with spatial position.

The following analytical expression via curve-fitting is derived based on the data contained in Fig. 4. A double Gaussian equation offers high fitting accuracy,

\[
S(r,z) = A(r)e^{-B(r)z^2} + C(r)e^{-D(r)z^2} \tag{12}
\]

where \( A, B, C, D \) are determined by the geometric shape of the electrode and radial position \( r \) of a charged particle inside the pipe. Combining equations (5) (10) and (12), we have,

\[
U_o(t) = \frac{k\,dt}{C} Q(t) = \frac{k}{C} \left[ \int q(r,\theta,z,t)[A(r)e^{-B(r)z^2} + C(r)e^{-D(r)z^2}] \, d\Omega \right] \tag{13}
\]

\[
U_o(t) = \frac{k\,dQ(t)}{C} = \frac{k}{C} \left[ \int q(r,\theta,z,t)[A(r)e^{-B(r)z^2} + C(r)e^{-D(r)z^2}] \, d\Omega \right] \tag{14}
\]

If the partial derivatives of \( q(r,o,z,t) \) and \( s(r,z) \) are existed and continuous, the sequence of integration and differentiation can be exchanged, so equation (14) can be rewritten as,

\[
U_o(t) = \frac{k\,dQ(t)}{C} = \frac{k}{C} \int \left[ \frac{\partial q}{\partial r} \frac{dr}{dt} + \frac{\partial q}{\partial \theta} \frac{d\theta}{dt} + \frac{\partial q}{\partial z} \frac{dz}{dt} + \frac{\partial q}{\partial t} \frac{dt}{dt} \right] \cdot S(r,z) + q \left[ \frac{\partial S}{\partial r} \frac{dr}{dt} + \frac{\partial S}{\partial \theta} \frac{d\theta}{dt} + \frac{\partial S}{\partial z} \frac{dz}{dt} \right] \, d\Omega \tag{15}
\]

Where \( \partial q/\partial r, \partial q/\partial \theta, \text{and} \partial q/\partial z \) are the distribution gradient along the radial, circumferential and axial coordinates of the charges carried by particles. \( dr/dt = V_r, \, do/dt = V_o, \text{and} \, dz/dt = V_z \) are the particle velocity projections at the radial, tangential and axial directions. In real powder pneumatic conveyance, the charges carried by the particle \( q \) is one of principal sources contributed to the detected signal, which is determined primarily by the solids concentration, \( q \) the partial derivatives of the spatial sensitivity \( s(r,z) \) are dependent upon the geometry of electrode and the location of particles. Besides, it can be seen that the output of the meter is affected by the velocities and the rate of change in charges carried by particles, because
the output of the meter is proportional to the derivative of the charges induced on the electrode.

4. EXPERIMENTS RESULTS AND DISCUSSIONS

The results were obtained using a belt rig and a 40mm diameter pneumatic conveying system at the laboratory of the University of Teesside to verify the theoretical analysis presented above. As it is known that the electrostatic charges carried by pneumatically conveyed particles depend on many factors such as humidity, particle size, and chemical compositions of the solids materials, in laboratory, it is difficult to control all of these variables. However if the results can be collected under the similar conditions, e.g. the similar humidity and temperature, and the solids are discharged completely in a recycling experimental system for each experiment, the results can be used to verify the effects of other factors such as velocity, air to solids ratio and solids location.

4.1 Experiments On Belt Rig

Fig. 5 shows a photograph of the belt rig in the laboratory of the University Teesside, which was used to validate the theoretical analysis discussed in Section 3. A rubber V-belt is wound around two pulleys, one of which is driven by a DC motor. The speed of DC motor is adjustable to set the belt velocity from 5m/s to 25m/s. A brush is attached to the rig frame, so that the electrical charges are generate when the belt passes through it. The charged belt is used to simulate a stream of charged particles travelling along axial direction. The diameter and the width of the electrode were 200mm and 2mm.

![Fig. 5 Conveyance belt rig](image)

The meter was placed on a hydraulic trolley so that the relative position of the belt to the sensor can be adjusted in the horizontal and vertical directions. The data were obtained using the specially designed data acquisition system, and the software program was developed using the National Instrument Labview package.
When the belt moving along the axial direction, restricted by the metal edge of the pulleys, the belt tangential velocity $dV_{un}/dt (V_0)$ is almost zero; When the charge on the belt saturated at a given motor speed, under the relatively dry air conditions, the charge on the belt within the sensing zone is essentially unchanged, so the variation rate of charge with time $dq/dt$ may be negligible. If we regard the property of rubber material is uniform along the belt, and the even distribution of charge along the belt can be resulted so that $dq/az$ is an odd function about $z$, so the integration of this item is also zero. Consequently, equation (15) can be simplified as,

$$U_o(t) = K \frac{dQ(t)}{dt} = K \int \left[ \frac{dq}{dr} \frac{dr}{dt} - S(r, z) + q \frac{dS}{dr} \right] d\Omega,$$

Let $I$ be the root mean square value of the sensor output voltage $U_o$ in one data acquisition period, and $I'$ be the average value of $I$ in much longer data acquisition periods, we have

$$I = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} U_o^2},$$

In figure 6 (a), curves 1,2,3,4 show the instantaneous values of $I$ when the belt ran at a fixed radial position at velocities of 7,9,11 and 13m/s respectively. Fig.6 (b) depicts that $I'$ increased with velocity over the range of $4 \sim 13 \text{ m/s}$. Fig.6 (c) gives the relationship between $I'$ and $r$ at a belt travelling velocity of $17 \text{ m/s}$. All these experimental results support the theoretical analysis in Section 3.

However what on earth caused the signal changes with the location and the velocity vector of the belt remains unclear. The following discussions may be useful for further investigations in this aspect.

There may be three reasons for the signal variation. At first, higher velocity means more intensive friction between the belt and the brush and between the belt and air, which produces more charges; secondly, it was observed that the belt vibration was significantly noticeable in the radial direction with the increased speed of the motor. The ratio of standard deviation to mean value of the signal was significantly higher than that at lower velocity. It can be seen from Equation (16) that the contribution of the radial movement of the belt represented by $dr/dt (V_r)$
may be very important and should not be neglected. In other words, even the charge carried by the belt unchanged, the signal could increase with $V_r$. In addition, due to the nonlinearity of function $s(r,z)$ and $as/az$, $I'$ varies nonlinearly with $r$.

4.2 Experiments On Pneumatic Conveying System

From the above discussion it can be seen that the output signal of an electrostatic flow meter is affected by many factors. The theoretical analysis can provide essential guidance, however the model can be optimised via calibration procedure. Here demonstrated is an example in which an electrostatic meter was calibrated under different air to solids ratios and solids mass flow rates, and a overall equation was found to govern the relationship between the meter output, solids mass flow rate and air to solids ratio.

A diagram of the test rig is shown in Fig. 7 and is based on the suction principle. The solids discharges into the test rig via the screw feeder shown in Fig.8, and the solids mass flow rate into the rig is determined from the ‘rate-of-loss’ of weight depicted in Fig.9. The air mass flow rate is obtained using an orifice plate located downstream of the cyclone i.e. in its exhaust.

The material used for the experiments was ‘Fillite’, a commercial product made of fly ash. The average particle size was about 100µm. The maximum solids mass flow rate was over 50kg/hr.

![Block diagram of the University of Teesside pneumatic conveyor](image1)

Fig. 7  Block diagram of the University of Teesside pneumatic conveyor

![Photograph of the screw feeder](image2)

Fig. 8  Photograph of the screw feeder
The air to solids ratio was kept approximately constant as the solids mass flow rate was varied for each sequence of tests and the signals were sampled over the selected measuring period, see Figure 10. The tests extended over the full operating range of the pneumatic conveyor and the process was repeated for air : solids ratios of 1.9:1 to 3.9:1.

Based on the test results in Fig. 11 and the theoretical analysis in Section 3, the relationship between air-solids ratio $R_{as}$, solids mass flow rate and the output signal $I^*$ for the in the vertical section of the rig can be expressed as,

$$I^* = F(R_{as}, M) = (A_1 R_{as} + A_2) M^2 + (B_1 R_{as} + B_2) M + (C_1 R_{as} + C_2)$$  (18)

Factors $A_1$, $A_2$, $B_1$, $B_2$, $C_1$, and $C_2$ are constants and were found via calibration using the data provided in Table 1. $A_1 = -0.1581$, $A_2 = 0.7908$, $B_1 = -14.826$, $B_2 = 61.511$, $C_1 = -290.05$, $C_2 = 1210.5$. 

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**Fig. 9**  Loss in weight characteristic

**Fig. 10**  Meter output-signal over a measurement period

**Fig. 11**  Calibration Data
### Table 1 Calibration data and calibration error

| Air/solid mass flow rate (kg/hr/kg/hr) | solids mass flow rate (kg/hr) | Meter calculated Output(mV) | absolute error (mV) | relative error % |
|---------------------------------------|-------------------------------|-------------------------------|---------------------|------------------|
| 3.78                                  | 27.38                         | 111.30                        | -2.11               | -1.93            |
| 3.88                                  | 33.12                         | 140.26                        | 7.46                | 5.05             |
| 3.79                                  | 37.80                         | 190.03                        | -6.34               | -3.45            |
| 3.83                                  | 43.28                         | 241.60                        | 0.61                | 0.25             |
| 3.95                                  | 46.69                         | 281.31                        | 8.20                | 2.83             |
| 3.91                                  | 51.85                         | 353.58                        | 3.10                | 0.87             |
| 3.3                                   | 32.85                         | 127.70                        | 2.61                | 2.01             |
| 3.32                                  | 37.76                         | 166.32                        | -3.69               | -2.27            |
| 3.32                                  | 43.03                         | 213.00                        | -1.68               | -0.79            |
| 3.38                                  | 47.44                         | 261.43                        | 5.19                | 1.95             |
| 3.38                                  | 52.38                         | 335.48                        | 0.92                | 0.27             |
| 2.85                                  | 37.79                         | 145.71                        | -3.84               | -2.71            |
| 2.86                                  | 42.82                         | 186.82                        | -3.44               | -1.87            |
| 2.88                                  | 47.71                         | 237.91                        | 3.37                | 1.40             |
| 2.38                                  | 37.75                         | 128.92                        | -7.95               | -6.57            |
| 2.38                                  | 42.21                         | 158.64                        | -6.82               | -4.49            |
| 2.4                                   | 46.44                         | 202.87                        | -5.12               | -2.59            |
| 2.39                                  | 52.00                         | 279.62                        | -1.92               | -0.69            |
| 2.39                                  | 57.60                         | 387.75                        | -2.41               | -0.63            |
| 1.91                                  | 47.10                         | 174.90                        | 2.48                | 1.40             |
| 1.9                                   | 51.38                         | 237.63                        | 3.66                | 1.52             |
| 1.91                                  | 56.43                         | 340.91                        | -1.01               | -0.30            |
| 1.96                                  | 438.59                        | 440.45                        | 0.42                | 0.10             |

It can be seen that the maximum relative error is less than 7%. It may be still too high for a single phase flow meter, but it is actually acceptable for a multi-phase flow meter.

### 5. CONCLUSIONS

The characteristics of the ring-shaped electrostatic meter has been analysed using the Finite Element Method and the electrostatic field theory. It concluded that the meter’s output depends on the location of the solids, the projections of the solids velocity on the axial and radial coordinates and solids concentration. These conclusions have been verified by experiments carried on the belt rig and the pneumatic rig at the laboratory of the University of Teesside, U.K. The paper also introduced a method to optimise the mathematic model via calibration. Although here provided are only results from meter 1, the equation also applies to other meters in vertical and horizontal sections. In industrial applications, if the air to solids ratio is known, and the output signal in the equation can be obtained from the meter, the equation can give a measured solids mass flow rate with an acceptable error.

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NOMENCLATURE

- $Q$: charge induced on the electrode [C]
- $U_i(t)$: input voltage of the conditioning circuit [V]
- $C_a$: capacitance of the electrode [F]
- $R_a$: insulation leakage resistance [Ω]
- $C_c$: stray capacitance of the cables [F]
- $C_i$: input capacitance of the conditioning circuit [F]
- $R_i$: input resistance of the conditioning circuit [Ω]
- $U_i(s)$: Laplace transform of $U_i(t)$
- $Q(s)$: Laplace transform $Q(t)$
- $U_i(j\omega)$: Fourier transforms of $U_i(t)$
- $Q(j\omega)$: Fourier transforms $Q(t)$
- $\omega$: angular frequency [rad/s]
- $C^*, C^{**}$: integration constants
- $C_F$: feedback capacitance of amplifier [F]
- $U_o(t)$: output of the meter [V]
- $\varphi(x, y, z)$: potential distribution [V]
- $\Gamma_p$: grounded pipeline wall [m$^2$]
- $\Gamma_c$: ring electrode [m$^2$]
- $\rho(x, y, z)$: charge density distribution [C/m$^3$]
- $\varepsilon_0$: dielectric constant in vacuum [$8.85 \times 10^{-12}$F/m]
- $\varepsilon(x, y, z)$: relative permittivity distribution of the powder material
- $E_\infty$: electric field strength at the infinite distance [V/m]
- $\Omega_r$: sensing zone of the electrode [m$^3$]
- $q(r, o, z, t)$: electrostatic charge noise [C]
- $s(r, o, z)$: space sensitivity distribution function
- $\partial q/\partial r$: charges distribution radial gradient [C/m]
\( \frac{\partial q}{\partial \theta} \) charges distribution gradient along the circumferential coordinate [C/rad]

\( \frac{\partial q}{\partial z} \) charges distribution gradient along the axial coordinate [C/m]

\( V_r \) velocity projection at the radial direction [m/s]

\( V_\theta \) velocity projection at the tangential direction [m/s]

\( V_z \) velocity projection at the axial direction [m/s]

\( I \) root mean square value of the sensor output voltage \( U_o \) [V]

\( \bar{I} \) the average value of \( I \) [V]

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