Profiling of pulverized fuel flow in a square-shaped pneumatic conveying pipe using electrostatic sensor arrays

S Zhang¹, S Wu¹, X Qian¹, Y Yan²,*

¹ School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China.
² School of Engineering and Digital Arts, University of Kent, Canterbury, Kent CT2 7NT, UK

* Corresponding author. E-mail: y.yan@kent.ac.uk

Abstract. Quantitative profiling of pulverized fuel flow in a pneumatic conveying pipe is essential to balance the fuel distribution and improve the operation flexibility of a coal-fired boiler. In this study, an electrostatic sensing head comprising square-loop shaped electrodes and strip-shaped electrodes is used to characterize the particle flow in a square-shaped pipe under various flow conditions. Cross-correlation and data fusion algorithms are also proposed to process and combine the multi-channel signals from the sensor arrays in the sensing head. Dynamic characteristics of the particle flow in a vertical square-shaped pipe on an experimental platform are presented. Experimental results demonstrate that the cross-sectional profiles of the velocity and volumetric concentration of particles in a square-shaped pneumatic conveying pipe are highly non-uniform.

1. Introduction
Square-shaped pneumatic conveying pipes are commonly used to transport pulverized materials in circulating fluidized beds and some power plants in recognition of the advantages of simple structure and easy installation [1]. Characterization of pulverized fuel flow in square-shaped pipes provides useful information about the flow for balancing fuel distribution, improving operation flexibility and optimizing the combustion process [2]. However, significant challenges are encountered due to the difficult nature of gas–solid two-phase flow in square-shaped pipes.

Particle flow regimes [3] and electric field distribution due to charged particles [4] in a square-shape pipe are more complex than those in a circular pipe because of its four sharp corners. Previous studies mainly focus on the dynamic characteristics of particles in a pneumatic transportation pipe through numerical simulations [5, 6]. Experimental investigations of particle flow in a square-shape pipe are scarce. In this study, for the first time, an electrostatic sensing head incorporating square-loop shaped electrodes and non-intrusive and intrusive strip-shaped electrodes is designed, constructed and tested. The methods for the signal analysis based on cross-correlation and data fusion are also proposed to characterize the velocity and volumetric concentration profiles of particles in a square-shaped pipe.

2. Sensor design and measurement principles
Figure 1 shows the physical structure and measurement zone partitions of the electrostatic sensing head. The sensing head includes three sets of electrode arrays (namely Array 1, Array 2 and Array 3).
Array 1 consists of two square-loop shaped electrodes with the same inner dimension of the pipe. Array 2 is composed of twelve pairs of strip-shaped electrodes that are uniformly embedded in the four flat pipe walls (namely Pair A to Pair L). Array 3 is comprised of nine pairs of strip-shaped electrodes, which are embedded into three independent, parallel sensor plates (namely Pair A’ to Pair I’).

The cross-section of the pipe is divided into nine measurement zones, i.e., four corner zones (Zones I, III, VII and IX), four zones along single pipe wall (Zones II, IV, VI and VIII), and one central zone (Zone V). The intrusive electrode pairs in Array 3 are placed in the central axis of the nine measurement zones, respectively. The square-loop shaped electrodes can sense the particles over the pipe cross-section [4] whilst strip-shaped electrodes provide only the local information about the particles nearer to the electrodes [7]. Accordingly, Array 1 estimates the “mean” velocity of particles across the whole cross section of the pipe, Array 2 characterizes the dynamic behaviors of particles closer to the outside area of each measurement zone, and Array 3 measures the particle flow in the central area of each zone.

**Figure 1.** Physical structure and measurement zone partitions of the electrostatic sensing head. (a) Physical structure, (b) Measurement zone partitions

In this study, cross-correlation velocity ($V_i$) [8] and root-mean-square (RMS) magnitude [9] combined with data fusion methods of the electrostatic signals are used to estimate velocity $V$ and relative volumetric concentration $\beta'$ of the particles. As for the “mean” velocity of the particles over the whole measurement pipe section, it equals to the cross-correlation velocity ($V_i$) from the two square-loop shaped electrodes in Array 1. Dynamic behaviors of the local particles in the outside area of each measurement zone are characterized by the electrodes in Array 2. For the four corner zones (Zones I, III, VII, IX), the velocity ($V_i$) and relative volumetric concentration ($\beta'_i$) are derived from the two adjacent electrode pairs:

$$V_i = \frac{V_{ij} \rho_j + V_{ik} \rho_k}{\rho_j + \rho_k}, \quad \beta'_i = \frac{\text{RMS}_j + \text{RMS}_k}{2}$$  \hspace{1cm} (1)

where subscript $i = I, III, VII$ and $IX$, subscripts $j,k = A, L$, or $I, J$, or $C, D$, or $F, G$, respectively. Correlation coefficients $\rho_j$ and $\rho_k$ are the velocity weighting factors. For Zones II, IV, VI and VIII, the velocity ($V_i$) and relative volumetric concentration ($\beta'_i$) are obtained from the adjacent electrode pair:

$$V_i = V_{ij}, \quad \beta'_i = \text{RMS}_j$$  \hspace{1cm} (2)

where $i = II, IV, VI$ and $VIII$, $j = K, B, H$ and $E$, accordingly. For Zone V, the characteristics of the velocity ($V_i$) and relative volumetric concentration are derived from the ones of the four adjacent zones, Zones II, IV, VI and VIII:

$$V_i = \frac{k'(V_{II} + V_{IV} + V_{VI} + V_{VIII})}{4}, \quad \beta'_i = \frac{k'(\beta'_{II} + \beta'_{IV} + \beta'_{VI} + \beta'_{VIII})}{4}$$  \hspace{1cm} (3)

2
where $k'_{v}$ and $k'_{c}$ are the dimensionless weighting factors (depend on the pipe configuration and flow characteristics, and can be achieved through calibration tests). The velocity ($V_i$) and relative volumetric concentration ($\beta'_i$) of the local particles in the central area of each zone equal to correlation velocity ($V_c$) and RMS obtained from the electrode pair of Array 3 placed in the corresponding zone, respectively.

3. Experimental tests and results

3.1. Test programme

Experimental work was undertaken on a laboratory test rig with square-shaped stainless-steel pipe sections, as shown in figure 2. The length and height of the test rig are 5100 mm and 2400 mm, respectively. The dimension of the inner side of the square-shaped pipe is 54 mm. An adjustable suction system is connected to the upper left side of the test rig to generate a stable flow and an adjustable double-screw feeder at the lower left side is used to feed test material into the rig. A prototype electrostatic sensing head was installed on a vertical section of the rig. The width of the electrodes in the sensing head is 3 mm whereas the length of the strip-shaped electrodes is 15 mm.

To comply with health and safety regulations of the laboratory environment, flour was used as a substitute of coal. The size of the flour particles is in a range from 98 μm to 124 μm and the bulk density is 0.52 g/cm$^3$. Experiments were undertaken with a constant air velocity at 27 m/s (reference air velocity in the centre of Zone V) and three different mass flow rates of 2, 4 and 8 kg/h (marked as M1, M2 and M3). The ambient temperature was around 16°C and the relative humidity was 10%. The values of dimensionless weighting coefficients $k'_{v}$ and $k'_{c}$ of particle flow in Zone V are determined as 1.15 and 1.02 using the intrusive electrode pairs in Array 3 under the same test conditions, respectively.

3.2. Results and discussion

The velocity profiles along with correlation coefficient profiles and relative volumetric concentration profiles of particles in a vertical pipe for different mass flow rates are depicted in figures 3 to 5. The legend label ‘SiMj’ means the results are taken from Array i under mass flow rate of Mj (i, j = 1, 2, 3). As can be seen from figure 3, the velocity profiles across the whole cross-section are non-uniform. The particles in the corner zones travel relatively slower than the particles in other zones in most cases due to the frictions between the particles and pipe walls. The effect of the centrifugal force, due to the upstream bend in the right lower side of the pipe, is also demonstrated, as particles in outside zones (Zones III, VI and IX) move faster than the ones in inside zones (Zones I, IV and VII). Meanwhile, the velocities obtained from Array 3 are higher than those from Array 2 in all cases, which means that the particles in the central area of each zone travel faster than those in the outer area of the corresponding zone.

![Figure 2. Layout of the pneumatic conveying test rig (not to scale).](image)

![Figure 3. Velocity profiles of particles.](image)
The velocities measured by Array 1 are within those from Arrays 2 and 3, but closer to the ones from Array 2, indicating that square-loop shaped electrode pair can measure the “mean” velocity of the particles, but is easily affected by the particles close to pipe wall. Furthermore, particle velocity decreases as mass flow rate of particles increases. The correlation coefficient profiles related to the velocity profiles are plotted in figure 4. Since higher correlation means more stable flow, the data depicted in figure 4 indicate that the particle flow in the central area of each zone is more stable than that in the outside area, and the particles in the corner zones are most unstable across the whole pipe cross-section.

Figure 5 shows the relative volumetric concentration profiles of particles. As can be seen, more particles traverse the outer zones (Zones III, VI and IX) because of the centrifugal force in most cases. The values of RMS from Array 2 are higher than the ones from Array 3, which means that the particles closer to the pipe wall carry more electrostatic charge than those in the central area of the same zone.

4. Conclusions
The electrostatic sensing head with square-loop shaped electrodes and non-intrusive and intrusive strip-shaped electrodes is capable of measuring the velocity and volumetric concentration profiles of particles in a square-shaped pipe. It has been found that the particles in the corner zones of the pipe cross section move slower but more unsteadily than those in other zones. The effect of centrifugal force due to the bend in the upstream has also been observed, as particles in the outer zones travel faster than those in the inner zones. Furthermore, the characteristic profiles of particles in different areas in the same measurement zone are also non-uniform, i.e., particles in the central area move faster and more steadily and carry less electrostatic charge than those in the outer area of the zone.

Acknowledgments
Authors wishing to acknowledge assistance from the Nation Natural Science Foundation of China under Grant 61603135. Mr. S. Zhang would also like to thank the IEEE Instrumentation and Measurement Society through the 2016 Graduate Fellowship Award.

References
[1] Liu S, Chen Q, Wang H, Jiang F, Ismail I and Yang W 2008 Flow Meas. Instrum. 16 135–44
[2] Qian X, Yan Y, Huang X and Hu Y 2017 IEEE Trans. Instrum. Meas. 66 944–52
[3] Adams J F W, Fairweather M and Yao J 2011 Comput. Chem. Eng. 35 893–900
[4] Peng L, Zhang Y and Yan Y 2008 Sens. Actuators A, Phys. 141 59–67
[5] Gao R and Li A 2011 Build. Environ. 2011 46 245–52
[6] Zhang H, Trias F X, Gorobets A, Oliva A, Yang D, Tan Y and Sheng Y 2015 Powder Technol. 269 320–36
[7] Zhang S, Yan Y, Qian X, Huang R and Hu Y 2017 IEEE Sensors J. 17 7516–25
[8] Qian X, Yan Y, Shao J, Wang L, Zhou H and Wang C 2012 Meas. Sci. Technol. 23 085007
[9] Coombes J R and Yan Y, 2015 Fuel 151 11–20