Particle size estimation of pulverized fuel in pneumatic pipelines using electrostatic sensing techniques

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Abstract. Particle size measurement of pulverized fuel (PF) provides useful data for efficiency improvement of a pulverizing system, optimization of fuel combustion and emission reduction on a fired power plant. This paper presents an experimental study of particle size estimation of pneumatically conveyed PF through electrostatic sensing. An electrostatic sensor head consisting of two narrow and one wide ring-shaped electrodes is designed and implemented to measure the PF velocity and quantify the features of the sensor signals. Experimental tests using particles with three different size ranges were conducted on the vertical pipe section of a 74 mm bore gas–solid two-phase flow test facility under various flow conditions. Test results show that the root-mean-square magnitude and power spectral density of electrostatic signals vary with particle size. For the same air velocity, the small change in particle velocity is an indication of particle size as the particle velocity decreases when the particle size is larger. The proposed method is capable of estimating PF particle size and has the potential to offer considerable advantages over its counterparts in power plant applications.

1. Introduction

On a pulverized fuel-fired power plant, the size of fuel particles in pneumatic pipelines not only reflects the performance and power consumption of a pulverizing mill, but also determines fuel combustion efficiency and the level of pollutant emissions. Therefore, particle size measurement of pulverized fuel (PF) in the primary air pipelines on a coal-fired power plant provides important diagnostic information to optimize the operating parameters of the pulverizing mill and conveying and combustion equipment.

Many attempts have been made for the development of online particle sizing techniques [1], such as those based on microwave, acoustic, laser, imaging, etc. However, most of them suffer from insuperable problems for long-time industrial applications. Therefore, online measurement of PF particle size remains a challenging problem [2]. In the absence of practical online methods, off-line instrumentation, such as laser diffraction or sieving equipment, is widely employed for PF size distribution analysis by taking PF samples from a pipeline. \( R_{90} \) and \( R_{200} \) that represent the total PF residue on the sieve with a mesh size of 90 \( \mu \)m and 200 \( \mu \)m, respectively, are two parameters usually referred on a fired power plant to evaluate the ignition reliability and combustion completeness of PF [2]. Electrostatic sensors have been used to measure gas–solid two-phase flows due to their advantages of reliability, convenient installation, high sensitivity, low cost, minimum maintenance requirement and intrinsic safety. Most of previous research was focused on the measurement of velocity,
volumetric concentration and mass flow rate of PF particles [3]. Zhang and Yan [4] demonstrated that the time and frequency domain features of the signal from a wire-mesh electrostatic electrode are associated with particle size. Further research using cylinder-shaped polyvinyl chloride (PVC) particles found that ratio between the electrostatic charge variation and particle size variation decreases with particle size [5]. This paper presents an experimental study of particle size estimation of pneumatically conveyed PF using electrostatic sensing techniques. A sensing head with two narrow and one wide ring-shaped electrodes was designed and implemented. Experiments on a 74 mm bore vertical pipeline using glass beads (as a substitute of PF) with different size ranges were conducted under various flow conditions.

2. Measurement principle
In gas–solid two-phase flows, particle size determines the chance of inter-particle and particle-pipe wall collision and particle friction with air stream. Therefore, the amount of electrostatic charge and velocity of a single particle is closely related to its size [4]. The electrostatic charge on the surface of a particle reaches a certain value during the conveying process [5,6]. Due to the gravitational effect, larger particles are expected to move slower than the smaller ones in the same conveying air stream. Therefore, the particle size of PF can be estimated by analyzing the signals from electrostatic sensors and the velocity of PF. As shown in Figure 1, a sensing head consisting of a pair of 2 mm width electrodes and one 10 mm electrode was designed and implemented in the present study. The narrower electrode pair, which has higher sensitivity and wider bandwidth, is used to obtain particle velocity based on cross-correlation velocimetry [3]. The wider electrode is adopted to obtain the electrostatic signal due to its larger sensing volume and better spatial filtering characteristics [7]. In this study, the root-mean-square (RMS) magnitude and power spectral density (PSD) of the signals derived from a 10 mm width electrode are used to establish their relationship with particle size.

3. Experimental tests and discussion
3.1 Test conditions
As shown in Table 1, experimental tests using fine glass beads with three different size ranges were conducted on a vertical pipeline under various air velocity and particle mass flow conditions. The glass bead is a substitute of PF to comply with health and safety regulations. The test conditions shown in Table 1 were determined according to the actual operation parameters of a power plant and the two important PF particle size parameters \(R_{90}\) and \(R_{200}\). The ambient temperature and relative humidity in the laboratory during the tests were 25.3°C and 40%, respectively.

| Particle Size (µm) | Air Velocity (m/s) | Mass Flow Rate (g/s) |
|-------------------|--------------------|---------------------|
| 50–100            | \(v_1\), 16        | 2.75                |
| 100–150           | \(v_2\), 20        | 4.17                |
| 150–200           | \(v_3\), 24        | 5.50                |
3.2 Results

Signals from the 10 mm wide electrode were obtained under various flow conditions. Figure 2 illustrates the comparison of the RMS magnitude of signals under different flow conditions. It can be seen from Figure 2 that the magnitude of the RMS increases with particle size and mass flow rate of particles and air velocity. The RMS magnitudes of the largest particles are 28%, 35% and 37% higher than those of the smallest particles under three air velocity conditions ($v_1$, $v_2$ and $v_3$), respectively, when the particle mass flow rate is 2.75 g/s. While similar discrepancies of 25%, 52% and 30% are obtained when the mass flow rate of particle increases to 5.50 g/s. As the particles speed up, the RMS also increases due to higher friction between air stream and particles and more intensive inter-particle interactions [8] and particle-pipe wall collisions. However, the increasing rate of the RMS for larger particles is smaller than that of smaller ones. The standard deviation (SD) of the RMS value increases with air velocity and remains relatively stable.

![Figure 2. RMS magnitude of the electrostatic signals under various flow conditions](image)

The RMS magnitude of an electrostatic signal depends also on many other factors such as moisture content, shape, physical structure, chemical composition of particles and pipeline material. Therefore, the PSD of the signal is further analyzed to identify the relationship between particle size and the frequency characteristics of the corresponding signal. Figure 3 shows the PSD of the electrostatic signals of particles under the mass flow rate of 4.17 g/s and air velocity of 24 m/s. As can be seen from Figure 3, the energy (quantified by the area enclosed by the X-axis and PSD curve) of the electrostatic signal increases with particle size, which is similar to the relationship between the RMS magnitude of the signal and particle size. The dominant peaks of the PSDs also increase with particle size as a result of more significant fluctuations of larger particles in the pipeline. However, the difference between the peak frequencies in the PSDs varies with particle size. The peak frequency of the particles ranged from 50 to 100 µm is 274 Hz, while the peak frequencies for larger particles are 461 Hz and 476 Hz, respectively. The small difference in the dominant peaks in the PSDs for larger particles brings difficulty for the size estimation of particle with the size greater than 100 µm.

![Figure 3. PSD of the electrostatic signals for particles with different size ranges (µm)](image)
The particle velocity is less affected by other factors compared to the electrostatic signal of particles due to its measurement principle [3]. Gravity has obvious effects on the velocity of particles in a vertical pipeline than in a horizontal one. Figure 4 shows the particle velocity measured by the pair of narrow electrodes for two different mass flow rates. It is clear that the particle velocity decreases with both particle size and mass flow rate. The maximum and average velocity difference between the two mass flow rates under all test conditions are 0.55 m/s and 0.18 m/s, respectively. The influence of particle size on particle velocity is greater than mass flow rate of particles. The slip velocity between conveying air and particles increases with particle size. The velocity difference of particles with different size ranges indicates that larger particle size causes greater particle velocity drops. It is also noticeable that particle size has a minimum effect on the particle velocity when the air velocity is 24 m/s for both mass flow rates of particles. The SD of particle velocity varies very little with both air velocity and particle size.

![Particle Velocity vs Particle Size](image)

**Figure 4.** Particle velocity under two mass flow rates of particles

4. Conclusion
The developed electrostatic sensing head is capable of obtaining the electrostatic signal and the velocity of particles under various flow conditions. Experimental results have shown that both RMS magnitude and dominant peak in the PSDs of the electrostatic signal increase with particle size when other flow conditions remain unchanged. For the same air velocity, the small change in particle velocity is an indication of the particle size as particle velocity decreases with particle size. Test results have demonstrated that the proposed method based on electrostatic sensing techniques is suitable for estimating PF particle size and, once fully developed, would offer significant advantages over its counterparts.

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References
[1] Archary H, Schmitz W and Jestin L 2016 *Chem. Process Eng.* **37** 175–197.
[2] Tolchinskii E N, Yu A and Lavrent’ev 2002 *Power Tech. Eng.* **36** 17–20.
[3] Qian X, Yan Y, Huang X and Hu Y 2017 *IEEE Trans. Instrum. Meas.* **66** 944–952.
[4] Zhang J and Yan Y 2003 *Powder Technol.* **135-136** 164–168.
[5] Yao J and Wang CH 2006 *Chem. Eng. Sci.* **61** 3858–3874.
[6] Matsuoka S, Maruyama H, Matsuyama T and Ghadiri M 2010 *Chem. Eng. Sci.* **65** 5781–5807.
[7] Xu C, Wang S, Tang G, Tang D and Zhou B 2007 *J. Electrostat.* **65** 582–592.
[8] Forward K M, Lacks D J and Sankaran R M 2009 *Phys. Rev. Lett.* **102** 028001.